HISTORY OF CULTURAL EUTROPHICATION AT LAKE MANITOU, INDIANA AND PROSPECTS FOR ITS MANAGEMENT

by

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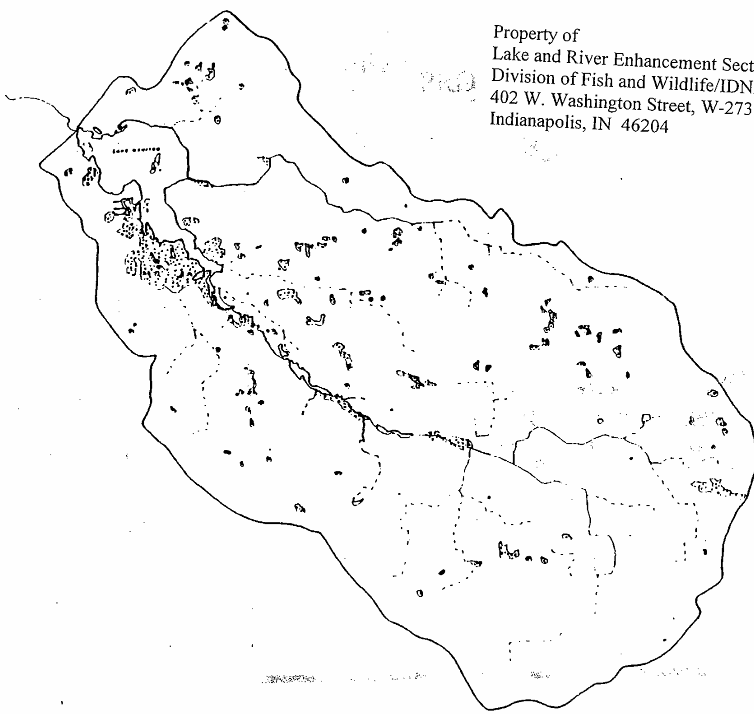

JANUARY 1987

HISTORY OF CULTURAL EUTROPHICATION AT LAKE MANITOU, INDIANA AND PROSPECTS FOR ITS MANAGEMENT

Submitted to the Lake Manitou Association

by

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January 1987

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INTRODUCTION

Eutrophication is an enhancement of the growth of either algae or aquatic macrophytes (weeds) when supplied with some limiting nutrient, normally phosphorus or nitrogen. While excessive plant growth in itself can cause problems, the secondary effects of eutrophication are often of equal concern. Foremost among these are health problems caused by bacteria and algal toxins, and alterations in the fish community whereby rough fish, such as gizzard shad and carp, replace game fish as dominants. Although many lakes are naturally eutrophic due to such factors as shallow depth, large watershed to lake area or phsophorus rich deposits, it is rapid man-induced cultural eutrophication that is of prime concern in most lake management studies. Crisman (1986a) has presented a detailed discussion of the causes and consequences of lake eutrophication.

During recent years, there has been growing concern among shoreline residents of Lake Manitou that the lake is experiencing progressive cultural eutrophication. Unfortunately, there is a noticeable paucity of historical data on the water quality of the lake that can be used to evaluate whether the lake naturally has always been extremely productive with little recent change in water quality or whether cultural eutrophication has accelerated recently to produce a marked visible change in overall water quality. If the latter is true, two cultural factors, residential development and agricultural practices, would appear to be potentially the most important contributors to enhanced lake productivity.

The major questions posed by lake residents have been: 1) What is the current status of the lake? Is it eutrophic?, 2) Is water quality getting progressively worse?, 3) When did the problem begin?, 4) What can be done either to keep the lake from getting worse or to improve water quality over today's condition? With these questions in mind, the present study was initiated to: 1) delineate the trophic history of Lake Manitou for the past 100 years as a means of separating the importance of natural versus cultural eutrophication as controlling factors for current water quality, 2) determine the factors that may be contributing to the perceived cultural eutrophication of the basin, 3) predict future changes in the water quality of the lake, and 4) provide management alternatives to prevent further deterioration of water quality from current levels.

A two-phase research plan was designed to address the above project objectives. First, all historical data on the water quality of the lake were assembled from the files of federal, state, and county agencies and interpreted. Second, paleolimnological techniques were employed to determine the trophic history of the lake for the past 100 years. Sediment cores for the latter research phase were collected in June 1985 from two sites in Lake Manitou. Selected levels in each core were dated with 210-Pb analysis so that the year of deposition of any level in the core could be approximated. Dating of cores was completed after one year to permit sufficient time for ingrowth of the 208-Pu isotope. Past water quality was reconstructed from sediment chemistry and animal microfossils for selected core levels. When combined with 210-Pb age determinations, one can tell not only how much water quality has degraded, but also when major events in this process occurred. Finally, data derived from sediment cores were related to known historical events including land clearance, population growth, dredging, etc. to estimate the importance of individual events on lake water quality.

The present report is a synthesis of data from previous investigations as well as the paleolimnological analyses described above that were conducted during 1985 and 1986. A series of recommendations pertinent to the future management of Lake Manitou to reduce cultural eutrophication are also provided.

HISTORICAL DATABASE FOR LAKE MANITOU

A total of twenty-six investigations were conducted on Lake Manitou between 1924 and 1986 (Table 1). The seemingly long record of data collection at the lake is deceiving because with the exception of the construction of a bathymetric map for the lake by the Indiana Department of Conservation in 1924, actual data collection on water quality in the lake did not begin until 1957. The Indiana State Board of Health conducted bacteriological surveys of the lake in 1957, 1958, 1959, 1960, 1964, 1965, and 1966, but only monitored additional water quality parameters during the 1957 and 1966 surveys. The 1957 survey measured water column dissolved oxygen, while the 1966 survey represents the earliest water chemistry data existing for the lake. In addition to temperature and dissolved oxygen profiles, this survey measured phosphorus, nitrogen, pH, alkalinity and major cations and anions. The only other investigation on Lake Manitou for the period of 1924-1966 was a single sampling of benthic invertebrates in the lake by J. Stahl (1959), a graduate student at Indiana University.

Beginning in 1967, the Fulton County Health Department assumed responsibility for bacteriological monitoring in Lake Manitou. This

TABLE 1. Chronology of investigations at Lake Manitou.

1924	Indiana Department of Conservation. Construction of bathymetric map of lake.
1957	Indiana State Board of Health. Bacteriological survey and water column dissolved oxygen.
1958	Indiana State Board of Health. Bacteriological survey.
1959	Indiana State Board of Health. Bacteriological survey.
1959	J. Stahl. Sampling of benthic invertebrates.
1960	Indiana State Board of Health. Bacteriological sampling at one site.
1964	Indiana State Board of Health. Bacteriological survey.
1965	Indiana State Board of Health. Bacteriological survey.
1966	Indiana State Board of Health. Bacteriological survey and monitoring of select cations and anions and alkalinity.
1967	Fulton County Health Department/Indiana State Board of Health. Bacteriological survey.
1970	Indiana Department of Natural Resources. Survey of fish populations, macrophytes, temperature, dissolved oxygen, pH, alkalinity, total phosphorus, nitrate, and select cations and anions.
1971	Indiana Department of Natural Resources. Selective gizzard shad removal with rotenone. Stocking of 5,000 2-3 inch largemouth bass.
1973	Indiana Department of Natural Resources. Survey of fish populations and alkalinity.
1975	Indiana Department of Natural Resources. Survey of fish populations, macrophytes, temperature, dissolved oxygen, pH, alkalinity, total phosphorus, total nitrogen.
1975	Indiana State Board of Health. Survey of algal species composition and abundance, Secchi disc transparency, temperature, dissolved oxygen, total phosphorus, total nitrogen for use in construction of BonHomme eutrophication index.
1977	Indiana Department of Natural Resources. Stocking of 2.5 million walleye fry.

TABLE 1 cont.

1979	Indiana Department of Natural Resources. Survey of fish populations, macrophytes, temperature, dissolved oxygen, Secchi disc transparency, pH and alkalinity.
1980	Indiana Department of Natural Resources. Stocking of 3099 northern pike.
1981	Indiana Department of Natural Resources. Stocking of 2.5 million walleye fry and survey of fish populations.
1982	Indiana Department of Natural Resources. Survey of fish populations.
1984	Indiana Department of Natural Resources. Survey of fish populations, macrophytes, temperature, dissolved oxygen, pH and alkalinity.
1984	Fulton County Health Department/Indiana State Board of Health. Bacteriological survey.
1985	Fulton County Health Department/Indiana State Board of Health. Bacteriological survey.
1985	T. Crisman. Collection of sediment cores for paleolimnological analyses.

agency conducted midsummer coliform monitoring surveys in the lake yearly between 1967 and 1969.

The most detailed data on water quality in Lake Manitou were collected after 1970. In that year the Indiana Department of Natural Resources (DNR) surveyed macrophyte and fish communities in addition to selected physical and chemical parameters of water quality. This study marks the earliest reasonably detailed survey of water quality parameters at Lake Manitou. Based on the results of this survey, the DNR initiated a selective removal of the rough fish, gizzard shad, in 1971 using rotenone, following which 5,000 largemouth bass fingerlings were stocked. The DNR returned in 1973 to monitor fish populations in order to evaluate the response of the fish community to shad removal and bass stocking.

The most extensive data collection on Lake Manitou occurred during 1975. In that year the DNR conducted their second survey of macrophyte and fish communities and select physical and chemical parameters, and the Indiana State Board of Health (ISBH) collected physical, chemical, and biological data on the lake as part of a statewide lake survey. The ISBH used these data for construction of the BonHomme eutrophication index, which is a way to quantify the water quality of Indiana lakes.

Since 1977 the DNR has been managing the fish community of the lake in an attempt to enhance gamefish populations. The DNR stocked 2.5 million walleye fry in 1977 and returned in 1979 to conduct their third survey of macrophyte and fish communities as well as select physical and chemical parameters. The initial gamefish stocking was followed by a stocking of 3,099 northern pike in 1980 and a second stocking of 2.5 million walleye fry in 1981. As part of the stocking program, DNR surveyed the fish community in 1981 and 1982 and conducted a fourth survey of macrophyte and fish communities and select physical and chemical parameters in 1984.

The final investigations at Lake Manitou have been the two bacteriological surveys conducted by the Fulton County Health Department in 1984 and 1985 and the collection of sediment cores as part of the current study in 1985. The recent efforts of the Lake Manitou Association to control aquatic macrophytes have been ommitted from consideration here because of an absence of data on these management practices.

A complete citation for each of the past investigations is provided in the reference section of this report, and xerox copies of data are available from T. Crisman upon request. Throughout the remainder of this report, the source of individual data points included in tables and figures has not been specifically identified. Rather, reference to the chronological listing of past investigations given in Table 1 should clarify the source of data for individual years.

HISTORICAL TRENDS IN PHYSICAL AND CHEMICAL PARAMETERS

The following section summarizes historical changes in the major physical and chemical parameters used to assess water quality. A number of terms used throughout the remainder of this report need to be defined initially. In lake management studies it is convenient to assign lakes to broad categories based on their water quality (trophic state). Clear water unproductive lakes that support little algae and aquatic weeds and have reduced fish abundance are termed oligotrophic.

Lakes of moderate algal/weed production and water clarity with well developed gamefish populations are termed mesotrophic. On the opposite end of the classification scale from oligotrophic systems are lakes that are extremely productive and experience either major weed management problems in shallow areas or prolonged periods during summer and fall when "scums" or blooms of blue-green algae cover the surface of the water and often form windrows of decaying organic matter along the shore. These lakes are termed eutrophic.

Temperature. Temperate zone lakes such as those of northern Indiana of sufficient depth have an annual thermal regime that is termed dimictic. This means that the entire water column theoretically mixes completely from top to bottom twice a year, once in the spring and once in the fall. For the remainder of the year, the lake is thermally and thus density stratified with bottom waters (hypolimnion) effectively isolated from mixed surface waters (epilimnion). The temperature transition zone between these two zones is termed the metalimnion. The duration of the mixing periods (turnovers) can be as short as a day or as long as a few weeks depending in part on the rapidity of temperature change and wind intensity.

Temperature profiles were constructed for the water column of Lake Manitou five times from 1970-1984 (Table 2). The investigations showed that the depth of the bottom of the well mixed surface waters (epilimnion) is between 10-12 feet in early summer (early July) and deepens to 20-22 feet in mid to late summer (late July to late August). Such a deepening of the epilimnion is expected in northern lakes as water temperature continues to increase throughout summer as a result of increased isolation and decreased night time temperature

TABLE 2. Depth to the bottom of the epilimnion in Lake Manitou for select dates during the period of 1970-1984.

Date	Top of the metalimnion (Feet)
20 July 1970	22 feet
7 July 1975	10 feet
20 August 1975	20 feet
30 July 1979	10 feet
9 July 1984	12 feet

loss to the atmosphere. Lake Manitou is thus deep enough to develop thermal stratification and should behave as a typical dimictic temperate lake. These data suggest that all areas of the lake deeper than approximately 20 feet should remain thermally and thus density stratified from late spring until mid fall.

Five areas of the lake meet this criterion and cover approximately 40 percent of the lake bottom (Figure 1). These represent the five natural lake basins that were artifically connected in 1827 when a dam was built at the mouth of the outlet stream thus raising water level to create the present Lake Manitou.

Oxygen. Since the bottom waters of a stratified lake (hypolimnion) are effectively sealed from the mixed surface waters (epilimnion) for a majority of the year because of temperature related density differences, the only time that oxygen is replenished in the deeper portion of the water column is during the short turnover periods of spring and fall. One way to assess whether a deeper lake is becoming or is eutrophic is to measure summer oxygen concentrations in the hypolmnion.

Algae produced in the surface waters of a lake eventually sink deeper into the water column and enter the hypolimnion where they will ultimately be decomposed using some of the oxygen that was supplied to the deep waters during the spring mixing period. By extension, the greater the algal population in the surface waters, the greater the quantity of organic matter entering the hypolimnion to be decomposed, and thus the faster the depletion of the finite summertime oxygen concentration of the hypolimnion. Eutrophic lakes usually have such high algal production rates that decomposition totally exhausts the hypolimnion oxygen supply (anoxia) early in summer. Oligotrophic

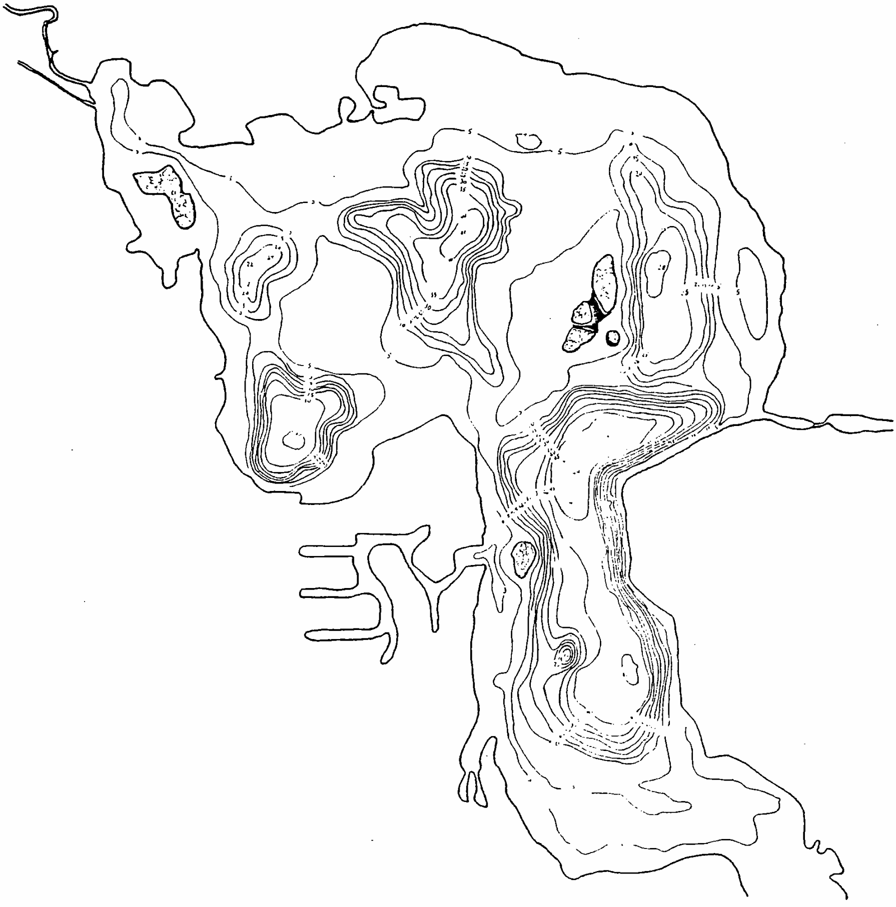

Figure 1. Lake Manitou in 1980.
Bathymetric data are from the 1924 map of the lake.

lakes, on the other hand, have such low algal abundance that hypolimnetic oxygen levels in late summer often approximate those at the end of the mixing period in late spring.

Summertime oxygen profiles were measured in Lake Manitou six times in the period 1957-1984 (Table 3). All six demonstrated the absence of oxygen (anoxia) below a water depth of 20-25 feet. The notable exception to this was on 20 August 1975 when anoxic conditions were found only below a depth of 40 feet. It appears that anoxic conditions develop yearly by early summer and persist until the fall mixing period. These data suggest that Lake Manitou has been highly eutrophic since at least 1957, the year of the earliest oxygen data.

Water Clarity. For a majority of natural lakes, there is a direct relationship between water clarity and the density of algal cells suspended in the water column (Wetzel 1975). This relationship was further demonstrated in a recent study of several Indiana lakes where the Indiana Stream Pollution Control Board found a significant statistical relationship between water clarity measured by a Secchi disc and the concentrations of algae in the water column estimated from chlorophyll *a* levels. A standard Secchi disc is a round plate 20 cm in diameter and painted with alternating triangles of white and black. When lowered in the water column, the depth at which the Secchi disc disappears from view is called the Secchi disc transparency and roughly approximates the depth where only 10 percent of the light striking the surface of the lake remains. This depth is normally considered to approximate the depth to which photosynthesis extends. Thus, the shallower the depth in the water column that the Secchi disc disappears from view, the more algae there are suspended and therefore

TABLE 3. Observations of hypolimnetic oxygen depletion in Lake Manitou from 1957-1984.

Date	Comment
22 August 1957	"One deep area of the lake was [illegible] devoid of dissolved oxygen."
20 July 1970	Anoxic below 20-25 feet
7 July 1975	Anoxic below 25 feet
20 August 1975	Anoxic below 40 feet
30 July 1979	Anoxic below 20 feet
9 July 1984	Anoxic below 25 feet

the more eutrophic the lake is.

Interpretation of Secchi disc data is complicated in those lakes and reservoirs characterized by a great deal of inorganic turbidity (suspended clay and silt) derived from watershed erosional processes. Although Lake Manitou often experiences periods of high inorganic turbidity in spring associated with snow melt and agricultural practices, all of the past Secchi readings discussed below were taken during summer, a period of low inorganic turbidity, and therefore should reflect principally the density of algal cells suspended in the water column.

Secchi disc transparency was measured four times in Lake Manitou for the period 1970-1984 (Table 4). Water clarity appears to have changed little during the period with readings of 3.5 feet in 1975 and 1984 and 4.0 feet in 1970 and 1979. Of the 331 Indiana lakes surveyed by the Indiana State Board of Health in 1975, 4 percent of the lakes had a Secchi depth of less than one foot, and the category that included Lake Manitou (1-5 feet Secchi) contained 33 percent of the lakes surveyed. The clearest lake surveyed was Saugany Lake in LaPorte County with a Secchi disc depth of 31.8 feet. On a category basis, 4 percent of the lakes were less clear than Lake Manitou, while 67 percent were clearer. On the basis of water clarity alone, Lake Manitou would fall into the eutrophic lake category.

pH. Researchers often use pH as an indicator of both the carbonate buffering capacity of a system and/or overall photosynthetic activity. A pH of 7 is considered neutral, while decreasing values from 7-0 indicate progressively acidic conditions and increasing values from 7-14 indicate progressively more alkaline conditions. In general, pH is increased by an increase in the concentration of

TABLE 4. Summary of physical and chemical measurements in Lake Manitou for the period of 1966-1984.

Parameter	1966	1970	1975	1979	1984
Secchi transparency (feet)		4.0	3.5	4.0	3.5
pH	8.3	7.75	8.25	8.5	8.5
Alkalinity	108	152	263	204	190
Total Phosphorus (mg/L)	.2	.2	.11 .04		
Nitrates	.425	$<.1$	$<.2$		
Calcium as $CaCO_3$	110	90	184		
Magnesium as $CaCO_3$	88	124			
Sodium		4			
Potassium	2	2			
Iron	$<.1$	$<.1$			
Manganese	$<.02$	$<.02$			
Sulfate		40			
Chloride	8.5	11			

buffering substances such as calcium as well as by increasing photosynthesis from algal and macrophyte communities.

Water column pH was measured in Lake Manitou during five years between 1966-1984 (Table 4). Although values for 1979 and 1984 (8.5 pH) appear to be slightly higher than recorded earlier (7.75-8.3) the change is not considered significant. The pH of a lake displays pronounced daily and seasonal differences related to photosynthetic activity and additional discrepancies are often seen between field and laboratory measurements of this parameter. Given the low frequency of sampling and the apparently minor inter year differences in reported values, it does not appear that pH has changed appreciably since at least 1966. The high values consistently recorded in Lake Manitou are similar to values recorded in hard water eutrophic lakes of the Midwest (Wetzel 1975).

Alkalinity. Alkalinity is a measure of the bicarbonate and carbonate content of water and therefore the buffering capacity of a system. This parameter is usually related to lake pH and is strongly influenced by both photosynthetic activity and the delivery of inorganic buffering compounds from the watershed.

Alkalinity was measured during five years between 1966 and 1984 (Table 4 and Figure 2). From a low value of 108 mg/L in 1966, values increased in 1970 to peak in 1975 at 263 mg/L. Post 1975 values have remained consistently higher (190-204 mg/L) than pre-1975 values (108-152 mg/L). Post 1975 values represent an increase in alkalinity of 11 percent over pre-1975 values.

It is suggested that this recent increase in alkalinity is controlled more by the delivery of buffering substances from the

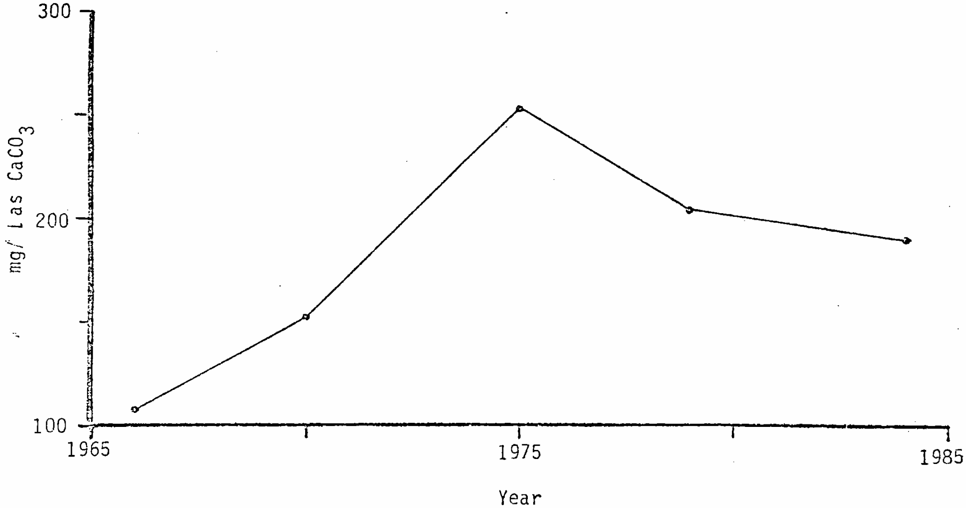

Figure 2. Total alkalinity (mg/L as $CaCO_3$) of Lake Manitou for the period 1966 - 1984.

watershed than by an increase in algal or macrophyte photosynthetic activity. The absence of a reduction in Secchi transparency between 1966-1984 argues against a pronounced increase of algal density and photosynthetic activity for the period, while the 84 percent increase in the calcium concentration in Lake Manitou between 1966-1970 and 1975 that will be discussed later supports the contention that the alkalinity increase is the result of an increase in the export of buffering substances and presumably inorganic sediments from the watershed between 1970 and 1975. As with the other parameters discussed earlier, the alkalinity values recorded in Lake Manitou are consistent with those of hard water eutrophic lakes of the Midwest.

Phosphorus. Algal and macrophyte photosynthesis is limited by the essential factor or element that is in least supply. Although temperature, light, nitrogen, and minor elements are important controlling factors (Wetzel 1975), the statistically significant relationship derived by Dillon and Rigler (1974) between phosphorus and chlorophyll a concentrations in lakes demonstrates clearly that the availability of phosphorus is the most important factor limiting the photosynthetic activity of algae and macrophytes in a majority of lakes. Thus, the more phosphorus that is added to a lake, the greater the growth and abundance of algae or weeds. Enhanced plant growth is normally interpreted as eutrophication and is assumed to be a reduction in water quality.

Total phosphorus concentrations were measured in Lake Manitou in 1966, 1970, and as part of two separate investigations in 1975 (Table 4). Values ranged from .04-.2 mg/L during the period, but it is felt that due to a paucity of sampling dates for any single year as well as potential differences in values due to differences in analytical procedures, such inter year differences in reported phosphorus concentrations are not significant. Values reported for 1975 (0.4 and .11 mg/L) by two separate agencies support this contention.

Of the 331 lakes sampled by the Indiana State Board of Health in 1975, Lake Manitou was included in a category (.1-.5 mg/L) that contained 32 percent of the lakes surveyed. Only 2 percent of the Indiana lakes were characterized by phosphorus values greated than .5 mg/L, while 66 percent of the lakes had values less than .1 mg/L. Based on the criteria established by the Indiana State Board of Health as well as those outlined in Wetzel (1975), Lake Manitou would be clearly classified as eutrophic on the basis of phosphorus concentrations alone. Phosphorus annual accumulation rates in the sediment calculated as part of the current paleolimnological project should provide a much clearer picture of historical trends in phosphorus for Lake Manitou.

<u>Other Water Chemistry</u>. Nitrate nitrogen was measured in Lake Manitou three times between 1966 and 1975 (Table 4). Values ranged from less than .1 to .425 mg/L for the period, but there appears to have been little significant change in values between years.

Calcium was measured three times between 1966 and 1975 and ranged from 90-184 mg/L (Table 4). Values recorded for 1975 (184 mg/L) represented an 84 percent increase over pre-1975 values (mean 100 mg/L). Although not measured in 1975, magnesium values for 1970 (Table 4) (124 mg/L) were 41 percent higher than for 1966 (88 mg/L). These trends support the contention stated earlier that the increase in watershed export of buffering substances most likely reflects increased erosion.

Other cations and anions have been measured only infrequently in Lake Manitou (Table 4). Sodium and sulfate were measured only in 1975, while potassium, iron, manganese, and chloride were analyzed both in 1966 and 1970. Where available, inter year differences in all parameters appear to be minor, but the paucity of the database for these chemical parameters precludes any detailed interpretation.

Trophic State Index. The Indiana Lake Classification Program was initiated in 1972 by the Indiana State Board of Health as a means of classifying lakes according to trophic state so that management strategies could be developed for either maintaining or restoring water quality. Each of several hundred lakes in the state were sampled at least once over the next five years. A total of ten parameters considered important trophic state variables were measured including total phosphorus, soluble phosphorus, organic nitrogen, nitrate, ammonia, dissolved oxygen, Secchi disc depth, photocell light transmission and phytoplankton abundance in the water column. A system of quantification was devised whereby the range of values possible for each parameter was divided into several subsets and each was assigned a numerical value called "eutrophy points". The sum of all eutrophy points for a given lake was used for construction of a trophic state index developed by Mr. Harold BonHomme of the ISBH and hereafter referred to as the BonHomme Eutrophication Index. The range of this index is 0-75 with 0 representing the least eutrophic (oligotrophic) and 75 the most eutrophic lake conditions possible.

The BonHomme index number calculated for Lake Manitou was 48, assigning the lake to ISBH Group III lakes. This group is composed principally of large shallow eutrophic lakes. The index range covered by this group was 23-48. Lakes of the worst water quality (index 50-

75) were included in Group IV. Of the total of 413 lakes included in the ISBH survey, 59 percent had index values between 25-60 with only 10 percent of the lakes having greater than 60. While Lake Manitou was not included in the lake group characterized by the worst water quality in the state, it defined the upper boundary for the lake group characterized by the second worst water quality. It is highly probably that since the collection of data for the index (1975), Lake Manitou has easily slipped into the group of worst water quality (Group IV).

HISTORICAL TRENDS IN BIOLOGICAL PARAMETERS

Bacteria. Analyses for total coliform bacteria in Lake Manitou were made on samples collected on 12 dates during the period 1957-1969 (Table 5). The current state standard for maximum permissible total coliform bacteria in water is 2400 cells/100 mL of water sample. This standard applies to those waters where whole body contact by humans occurs. The earliest total coliform bacteria data were for two dates in late summer of 1957. A total of 33 stations were samples of which 20 exceeded the state standard of the time of 1000 cells/100 mL. The ISBH returned one year later in August 1958 and reported that there was "no improvement in the situation" of the year before. In his correspondence with Dr. Stinson, the Fulton County Health Officer, Mr. Oral Hert of ISBH noted that "although a few of the lake residents have improved their sewage disposal facilities, it is apparent that it is necessary for all property owenrs to provide proper disposal for sewage and wastes before material improvement will be shown in Lake Manitou. The apathy toward sewage pollution demonstrated by the majority of the lake residents has hindered the efforts of your office, the Lake Manitou Association, and the State Board of Health. I

TABLE 5. Analyses of total coliform bacteria in Lake Manitou 1957-1969.

DATE	# STATIONS SAMPLED	# STATIONS EXCEEDS STATE STANDARDS 2400/100ml	RANGE (#/100ml)	MEAN (#/100ml)
8/22/57 9/4/57	33	20*	430-43,100	
8/25/58	"No improvement in the situation."			
July 1959	"Most samples ... were well within the 'safe' range."			
7/6/60	1	1	15,000	15,000
7/14/64	11	8	750-43,000	22,568 ± 27834
7/28/65	19	5	36-23,000	2,752 ± 5456
7/12/66	3	3	3,140-5,684	3,996 ± 1461
July 1966	17	8	230-23,000	4,309 ± 5573
7/12/67	19	9	91-23,000	4,086 ± 5343
7/22/68	22	1	10-2,700	413 ± 570
7/2/69	27	4	70-9,200	1,151 ± 1877
8/5/69	6	0	10-1,300	261 ± 511

* Greater than standards of the time of 1000/100 ml.

don't believe these people would be so unconcerned if they were aware of the potential health hazard existing for the hundreds of children swimming in this lake." The ISBH again sampled the lake in July 1959 and noted that "most samples...were well within the safe range".

The first sampling of the 1960's was at a drain tile entering the lake at the boat launching site. On 21 June 1960 a bacteria count of over 15,000 cells/100 mL was found. Mr. Orem of the ISBH attributed this high count to the fact that the tile drained an agricultural area and the matter was dropped. Eleven stations were sampled on 14 July 1964, 8 of which exceeded the state standard of 2400 cells/100 mL. The most serious bacteria counts were offshore from two cottages, the Tainman's Lodge and at the mouth of the "new channel". The latter site undoubtedly refers to the finger canal system dredged along the southwest shore. This canal system was created prior to 1962 because it appears on the USGS topographic map of that year. Five of the 19 sites sampled the next summer on 28 July 1965 exceeded state standards with the public boat ramp area, as in 1960, included with over 9,300 cells/100 mL.

Total coliforms were surveyed twice in 1966. Three stations, location unspecified, were sampled on 12 July. All three exceeded state standards with a mean value for the date of 3,996 cells/100 mL. The second sampling for 1966 was for 17 stations, but the exact date of sampling was not given. If the ISBH followed the practice of previous years, the sampling occurred near the end of July. Eight of the stations exceeded state standards on the date in question with a high of 23,000 cells/100 mL being recorded. As in many of the previous surveys, values of the White Creek sample clearly exceeded state standards, and the sample from the mouth of Rain Creek at the south end of the lake was 100 cells from the state standard of 2,400 cells/100 mL.

The final year that excessively high total coliform counts were recorded throughout Lake Manitou was 1967. Samples were collected on 12 July 1967 at 19 stations. Nine of these exceeded state standards. As in previous years, state standards were exceeded at the mouth of White Creek and approximately 100 cells/100 mL from exceeding permissible levels at the mouth of Rain Creek.

In October 1962, the Fulton County Commissioners passed and adopted Ordinance SD-1, an ordinance regulating installation, construction and operation of private sewage systems. Earlier, in January 1960 the Fulton County Health Department was established and assumed much of the responsibility from the ISBH for investigation and enforcement of sewage violations in the county. It is felt that these two events did much to alleviate the sewage contamination problem at Lake Manitou. By the 22 July 1968, only 1 of the 22 stations monitored exceeded state standards, and this was by only 300 cells/100 mL. Similar reductions in total coliform bacteria counts were noted on 2 July 1969 when only 4 of the 27 stations sampled exceeded state standards and again on 5 August 1969 when none of the 6 stations had excessive bacteria numbers. No data on total coliform bacteria counts were found post 1969.

The Indiana state standard for excessive fecal coliform bacteria in waters where whole body contact by humans occurs is 400 cells/100 mL. Data on analyses of fecal coliform bacteria in Lake Manitou were found for 13 dates between 28 July 1965 and 3 September 1985 (Table 6). Of the total 76 stations sampled over the twenty year period, only 3 stations exceeded state standards. At least since 1965, there

TABLE 6. Analyses of fecal coliform bacteria in Lake Manitou.

DATE	# STATIONS SAMPLED	# STATIONS EXCEED STATE STANDARDS 400/100ml	RANGE (#/100ml)	MEAN (#/100ml)
7/28/65	19	1	0-500	70.52 ± 122.7
7/12/65	2	0	25	25
7/12/67	8	0	10-60	25 ± 22
7/2/69	27	1	10-1,400	63 ± 267
5/29/84	1	1	990	990
6/18/84	3	0	10-50	23 ± 23
7/2/84	3	0	10-30	16 ± 11
12/17/84 12/19/84	2	0	220-390	305
4/16/85	2	0	10-100	55
6/26/85	3	0	10	10 ± 0
7/1/85	3	0	10-230	83 ± 127
9/3/85	3	0	10-100	40 ± 51

appears to have been no problem with fecal coliform bacteria levels in the lake.

Macrophytes. Aquatic macrophytes (weeds) were surveyed four times during the period 1970-1984 (Table 7). Although detailed data on the total and species abundance of macrophytes are totally lacking, we do have a good listing of the species composition of the community. Four habitat types characterize aquatic macrophyte communities. Emergent macrophytes are those which are living near shore and are rooted in the substrate with all of their leaves and flowers above the water surface. These are limited in their water depth distribution by how far they can send their stems up to insure that leaves and flowers are above the water. Floating leaved macrophytes are those that are rooted in the substrate, usually have an underground tuber, and produce long stems to place their leaves on the water surface. As with the emergents, floating leaved plants are limited in their depth distribution in lakes by the length of stem they can produce. Submergent macrophytes are firmly rooted in the substrate, but unlike the two groups just discussed, keep all vegetative growth below the water surface. It is this group of macrophytes that causes most of the management problems in temperate lakes. The fourth and final group of macrophytes are the free-floating plants that possess only vestigial roots and float on the water surface. These plants gain all their nutrients from the water and reach their maximum extent in eutrophic lakes. Although not a problem in northern lakes, this group of plants is of special management concern in southern lakes. A final plant group that is often discussed along with macrophytes is the macroalgae. These plants are attached to the bottom, they are more closely related to the algae suspended in the water column than they

TABLE 7. Aquatic macrophytes of Lake Manitou.

		1970	1975	1979	1984
Emergent and Floating Leaved:					
Spatterdock	Nuphar advena	X	X	X	X
White lily	Nymphae tuberosa	X	X	X	X
Arrowhead	Sagittaria spp.	X	X	X	X
Bullrush	Scirpus americanus	X	X	X	X
Cattail	Typha latifolia	X	X	X	X
Submergent:					
Water milfoil	Myriophyllum spp.	X	X	X	X
Coontail	Ceratophyllum demersum	X	X	X	X
Sago pondweed	Potamogeton pectinatus	X	X	X	X
Eel grass	Vallisneria americana				X
Free-Floating:					
Duckweed	Lemna spp.	X	X	X	X
Macroalgae:					
Chara	Chara spp.	X	X	X	X

are to the above mentioned groups of vascular plants.

Macrophytes are needed as fish habitat in lakes. Unfortunately, during the eutrophication process macrophytes often expand both aerially and vertically in the water column. Serious management problems can result when dock areas and shallow water zones become so clogged with weed growth that navigation becomes impaired. Lakes becoming progressively more eutrophic may go through a period when the biomass of both algae and macrophytes increase in response to nutrient addition. Ultimately, one or the other of these two communities will completely dominate the system. As pointed out by Crisman (1986a), radical destruction of weed biomass in macrophyte dominated lakes often releases nutrients so fast that there is a rapid expansion in blue-green algal populations. This enhanced biomass then shades out the remainder of the macrophyte community, and the lake shifts to complete algal dominance. Once a lake shifts to algal dominance, it becomes extremely expensive and often totally impossible to re-establish a balance between algal and macrophyte communities. It is for this reason that any future management of macrophyte populations in Lake Manitou be approached with a great deal of caution.

There appears to have been little alteration in the species composition of the macrophyte community between 1970 and 1984 (Table 7). Two species of floating leaved plants have always been common in shallow areas of the lake, spatterdock and white lily, as have three taxa of emergents, arrowhead, bullrush, and cattail. The free-floating plant, duckweed, appears to be limited to quiet protected areas near shore and does not appear to have been a problem in the past. Chara is the only macroalga recorded in the lake. This genus is characteristic of hard water lakes, and its presence confirms the validity of the alkalinity data presented earlier.

Management problems in Lake Manitou have always been associated with the submergent macrophyte community. Four taxa are common in the lake and include water milfoil, coontail, sago pondweed, and eel grass. Of these, the most likely candidates for past problems in the lake are coontail and water milfoil. Coontail (Ceratophyllum) is a native plant that often expands in shallow water in response to increased nutrient availability, but it is likely that most of the management problems have been associated with excessive growth of water milfoil (Myriophyllum). Although there are several native species of this genus in Indiana, most weed management problems in northern lakes have been associated with the exotic species called Eurasian watermilfoil (Myriophyllum spicatum). Implications of aquatic macrophyte control on the cultural eutrophication of Lake Manitou will be discussed later in this report.

Algae. Both the abundance and species composition of algal communities are related to lake trophic state. Clear water unproductive lakes (oligotrophic) are characterized by extremely low algal abundance and dominance by species of green algae and diatoms. At the opposite end of the trophic spectrum, extremely productive lakes (eutrophic) are characterized by excessive algal abundance with species of blue-green algae dominating the assemblage.

Algal data were collected on Lake Manitou twice, 1957 and 1975. Total algal abundance for 22 August 1957 was reported at 1,800/mL while that of 20 August 1975 was 12,500 cells/mL in the epilimnion and 9,000 cells/mL deeper in the water column in the metalimnion. Strict comparison of these two dates is not possible because, while the 1975 data are reported in standard scientific format, the tabulation methodology for the 1957 data were not given. The 1975 data approximate levels characteristic of eutrophic lakes of the Midwest in late summer, while the 1957 data appear to be low (Wetzel 1975).

Data on the taxonomic composition of the algal flora were provided only for the sampling of 20 August 1975 (Table 8). Although a total of five groups of algae were identified from the lake, most of the taxa belonged to the blue-green and green algal groups. Three taxa considered problem causing in many northern lakes, Anacystis, Aphanizomenon, Lyngbya, and Microspora dominated total algal abundance. Evidence for the great photosynthetic activity of this algal assemblage is provided by the supersaturation of dissolved oxygen in the water column to depth of five feet on 20 August 1975. In such situations, oxygen is released by algae during photosynthesis faster than it can dissipate into the atmosphere and the water column contains more oxygen than is theoretically possible.

It is most unfortunate that such an important biological parameter as algae was measured so infrequently and imprecisely in the past. The data that are available do indicate, however, that both macrophyte and algal communities are extremely productive with a delicate balance between the two for dominance of the lake. It can not be overemphasized that any misguided attempts to control either algae or macrophytes could have disastrous effects on the lake ecosystem. I am especially concerned with radical removal of macrophytes from the lake. The nutrients thus released could easily stimulate the growth of the nuisance algal taxa that are already dominant in the lake, thus causing an even more serious management problem than already exists in

TABLE 8. Phytoplankton taxa collected in Lake Manitou on 20 August 1975.

Blue-green Algae:

Anacystis

*Aphanizomenon

Lyngbya

Green Algae:

Chlorella

Scenedesmus

*Microspora

Staurastrum

Diatoms:

Synedra

Dinoflagellates:

Ceratium

Euglenoids:

Euglena

*Dominant taxa

the lake.

Benthic Invertebrates. The benthic invertebrate assemblage of lakes consists of both those organisms such as worms and bryozoans that spend their entire life as aquatic forms and insect larvae including chaoborid and chironomid midges that emerge from the lake as terrestrial flying adults to mate and deposit their eggs on the surface of a lake or pond. In general, the aquatic insects display the greatest degree of taxonomic diversity and usually dominate the biomass of invertebrate assemblages in most lakes.

Benthic invertebrates serve as an important food item for most gamefish and have been used extensively in water quality investigations. Dominance of benthic invertebrate communities in eutrophic lakes shifts to those forms that possess either more efficient oxygen-transport pigments (hemoglobin) or are capable of going dormant during periods of oxygen stress in the summer. Community changes are also associated with habitat alteration such as a shift to more organic-rich sediments and alterations in the community structure of rooted macrophytes.

Given the extreme value of benthic invertebrates in water quality assessment, it is most unfortunate that the single sampling of J. Stahl, a graduate student at Indiana University, in 1959 represents the only time that this biological parameter has been investigated. At that time the dominant midge was Chironomus semireductens, and three species of chaoborids, Chaborus albatus, C. flavicans, C. punctipennis, were abundant. Chironomus is usually thought of as a dominant in eutrophic lakes, and the presence of abundance chaoborid larvae is commonly associated with the development of summertime anoxia in deep waters (hypolimnion). A much clearer picture of the historical changes in the benthic invertebrate community will be presented as part of the paleolimnological investigations discussed later in this report.

Fish. The fish community of Lake Manitou was surveyed by the Indiana Department of Natural Resources in 1970, 1973, 1975, 1979, 1981, 1982, and 1984. Unfortunately, data for 1973, 1981, and 1982 were unavailable for inclusion in this present report. Recently the DNR has initiated a sport fish enhancement program. The first phase of this program was the selective removal of the rough fish, gizzard shad, with the natural toxicant rotenone in 1971. In that year 5,000 largemouth bass fingerlings 2-3 inches long were also stocked following shad erradication. Prior to the erradication program, it was felt that a majority of the shad population was of a size too large (11-12 inches) to be eated as forage by the gamefish population. By eliminating the large individuals with rotenone, it was hoped that the largemouth bass subsequently stocked would feed on any offspring from the remaining residual shad population and thereby keep this troublesome fish in check.

As a result of the 1975 fish survey, the DNR noted that the gizzard shad was again abundant in the lake and that few of the bass stocked in 1971 were still present. They did note, however, that the overall bass population had increased over that of 1971. Their 1975 report suggested that additional predator fish, especially northern pike and walleye pike, be stocked to help control both the gizzard shad and small sized panfish.

The first stocking of predator fish by DNR took place in June 1977. In that month a total of 2.5 million walleye fry were released into Lake Manitou. Although annual spot checks were made each fall and a detailed fish survey was made in 1979, none of the fish of this first stocking were collected by DNR field teams. A total of 3,099 northern pike were stocked during 1980, and subsequent DNR checks in 1981 and 1982 indicated good survival and growth. The success of the northern pike stocking program was further documented during the 1984 DNR fish survey when it was suggested that the pike stocked in 1980 had begun to reproduce in the lake. A second stocking of walleye pike (2.5 million fry) was made in 1981, but I was unable to obtain information regarding the success of this second attempt to establish this fish in Lake Manitou.

The contribution of individual taxa to total fish abundance in Lake Manitou for the period 1970-1984 is provided in Table 9. On a numerical basis, bluegill has always been the dominant fish in the lake comprising 27-34 percent of total abundance. With the exception of gizzard shad, black crappie, golden shiner, and brown bullhead, the percent contribution of individual taxa to total fish abundance remained relatively constant between 1970 and 1984. Ranging between 7.8 and 12.1 percent of total abundance during the 1970's, the black crappie had increased to 22.3 percent by 1984 making it the second most abundant fish in the lake. The golden shiner declined progressively in importance from 4.2 percent in 1970 to 2.3 percent in 1984, but this approximately two percent change is likely not to be a significant change. Conversely, the brown bullhead increased progressively during the same period from 2.4 to 12.2 percent of total abundance. Unlike the golden shiner, it is more likely that this represents a significant change in the relative dominance of this species.

TABLE 9. Percent of total fish abundance in Lake Manitou contributed by individual taxa.

	1970	1975	1979	1984
Bluegill	34.0	30.6	38.2	27.0
Gizzard Shad	30.8	21.7	+	11.8
Black Crappie	12.1	7.8	9.1	22.3
Golden Shiner	4.2	3.8	3.3	2.3
Largemouth Bass	3.8	6.0	3.1	6.0
Yellow Perch	2.8	9.5	10.6	3.5
Brown Bullhead	2.4	6.4	9.0	12.2
Yellow Bullhead	2.1	1.3	5.5	.9
Redear Sunfish	1.9	1.9	8.0	2.3
Lake Chubsucker	1.5	1.7	1.2	.1
Spotted Gar	1.3	2.2	1.4	4.2
Pumpkinseed	1.0	3.9	3.9	1.6
Warmouth	.7	1.0	2.4	1.4
White Sucker	.5	.4	+	.1
Bowfin	.5	.5	+	.5
Longear Sunfish	.2	.1	+	.3
Hybrid Sunfish	.2	.1		
Grass Pickeral	.1	.2	+	
Brook Silversides	*	*	*	*
Rock Bass		.5	1.1	1.2
Carp		.3	+	.4
Mud Minnow		.2		
Longnose Gar			+	
Black Bullhead			+	
Northern Pike				1.5
Golden Redhorse				.1

* Abundant but not included in percentage calculations.

\+ Less than 1% of total abundance.

The gizzard shad is potentially the most detrimental fish in the lake today. Based on a finding of 34 percent of total fish abundance being contributed by gizzard shad in 1970, the DNR initiated a selective eradication of this species using the toxicant rotenone in 1971. As stated earlier, bass were then stocked to feed on the offspring produced by any residual population of shad thereby preventing maturation of the population to a body size too large to be consumed by predator fish. The 1975 DNR survey indicated that despite an apparent increase in the bass population, few of the individuals stocked in 1971 remained in 1975. By 1975, the shad population was making a come back to comprise 21.7 percent of total fish abundance. Walleye were stocked (2.5 million fry) in 1977 in an attempt to keep the gizzard shad in check, but this stocking was unsuccessful. By 1979, however, the gizzard shad population was reduced to less than one percent of total fish abundance. The DNR attributed this marked reduction to winter kill during the severe winters of the previous three years. In spite of the stocking of 3,099 northern pike in 1980 and a second stocking of 2.5 million walleye fry in 1981 to enhance predation pressure on this species, the gizzard population again demonstrated its resilience and increased to 11.8 percent of total fish abundance by 1984.

Gizzard shad are of concern because an important part of their diet is algae. Gizzard shad are absent in oligotrophic lakes because there is not sufficient algae to support them. In mesotrophic and especially eutrophic lakes, algal populations are sufficient for the fish to become established. Shad feed by filtering water through their gills and ingesting the collected algae. The problem is that the acidity in the fish's stomach is insufficient to digest blue-green algae, and these unwanted algae pass through the fish alive, while beneficial algae such as diatoms and green algae are consumed (Crisman and Kennedy 1981). Thus, once shad are established in a lake, they promote dominance of algal assemblages by blue-green species and stimulate the development of eutrophic conditions.

Carp is the second potentially detrimental fish in Lake Manitou. Carp is undesired not only because it is not a sport fish, but because it mixes bottom sediments during its feeding activities, thus enhancing phosphorus release to the water column. Such phosphorus is then available for algal utilization. Fortunately, carp has made up less than one percent of total fish abundance in Lake Manitou for the entire period 1970-1984. Both gizzard shad and carp are fish characteristic of eutrophic lakes. It is likely that if the eutrophication of Lake Manitou is not checked, both species will assume greater dominance of the fish assemblage in future years. Strong public support for the DNR efforts to control shad populations is vitally needed.

Data on the growth and general conditions of important fish species in Lake Manitou for the period 1970-1984 are provided in Table 10. Growth refers to the length of individuals of a given age class, while condition is the relation between weight and length and thus is a measure of the plumpness of individuals relative to their age and length. Largemouth bass were of average growth and condition in 1970 but since that time have displayed below average growth. Both the condition and growth of bluegill, however, improved between 1970 and 1975 and have displayed values considered average for lakes of northern Indiana since that time. With the exception of 1979, growth

TABLE 10. Growth and general condition of important fish taxa in Lake Manitou. Parameters are scored according to below average (-), average (0), and above average (+) relative to other fish populations of northern Indiana.

	1970	1975	1979	1984
Largemouth Bass				
Growth	0	-	-	-
Condition	0	-	0	0
Bluegill				
Growth	-	0	0	0
Condition	-	+	0	0
Yellow Perch				
Growth	-	-	0	-
Condition	0	0	+	0
Black Crappie				
Growth	-	-	0	-
Condition	+	+	0	0
Redear Sunfish				
Growth	+	+	+	
Condition	+	+	-	
Northern Pike				
Growth				+
Condition				+

of yellow perch has been below average, while the condition of the population has been average or slightly above. Black crappie displayed the same pattern for growth as yellow perch. The general condition of this species, however, was above average in 1970 and 1975, but declined to values considered average for northern Indiana lakes during both 1979 and 1984. With the exception of below average condition in 1979, both growth and condition of the redear sunfish population were above average for the period 1970-1979. Finally, the northern pike population stocked in 1980 appears to be doing well as evidenced by the above average growth and condition values for 1984.

In summary, the gamefish population of Lake Manitou appears to have changed little in the past 17 years and is considered generally healthy. While the walleye stocking was unsuccessful, that of northern pike appears to have succeeded. Ominous signs of potential detrimental change in the fish fauna are shown by the persistence and resilience of the gizzard shad population. Further eutrophication of Lake Manitou can only encourage the growth of this species. While additional fish data for the lake would be highly desirable, the public must realize that detailed fish surveys require great expenditures of both manpower and money.

PALEOLIMNOLOGICAL PERSPECTIVE ON EUTROPHICATION

The value of paleolimnological techniques in applied ecological research has been reviewed by Crisman (1978, 1987) and Binford et al. (1983). In particular, this research approach has been invaluable in understanding lake responses to eutrophication and acid rain. The premise of the paleolimnological approach is simple. Each year a record of the current chemical and biological status of a lake is deposited in the top layer of sediments collecting on the lake bottom. The progressive sediment accumulation of successive years caps this annual record, thus preserving it much like the individual pages of a history book. By isotopically dating sediment cores so that the year of deposition of any level in the core can be determined, the researcher can use information gathered from physical, chemical and biological markers at any core level to reconstruct lake conditions at the time of deposition. Changes in the past condition of the lake can then be related to known historical records of human activity that may have been responsible for the changing lake condition. For a majority of lakes in the world, the history of water quality is either not extensive or lacks sufficient quality control as to not supply a database sufficient to delineate factors responsible for perceived or actual environmental degradation of a lake. In such cases, the paleolimnological approach is the only feasible way both to reconstruct the environmental history of a lake and to relate it to known human activity.

Sediment cores were collected at each of the four deepest holes of Lake Manitou on 24 June 1985. Cores from several of the sites were rejected because of the highly soupy nature of the sediment. Such sediments would have been highly mixed and therefore inappropriate for detailed stratigraphic studies. One core from each of two sites were chosen for the paleolimnological investigation reported here (Figure 3). The first core, designated Core E, was collected east of Big Island in 24.8 feet (7.58 meters) of water. The second core, Core W, was collected west of Big Island in 34.61 feet (10.55 meters) of water. Numerous residents told of the water east of Big Island

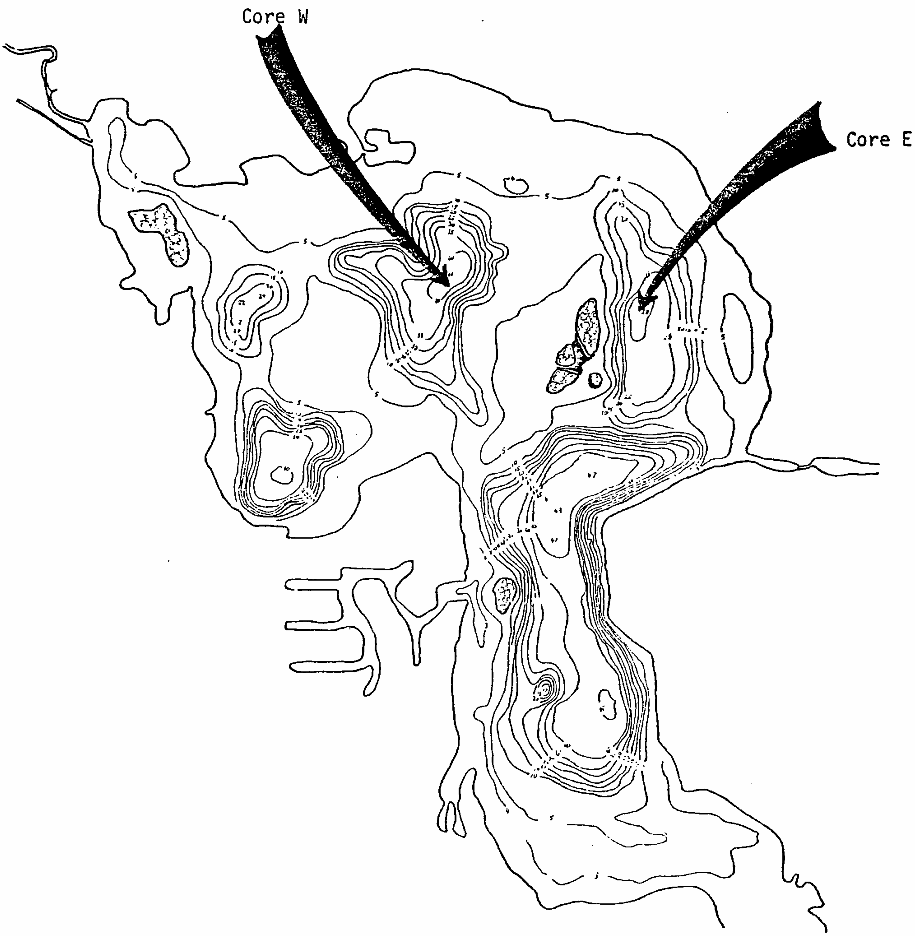

Figure 3. Site locations for sediment cores collected from the eastern and western basins of Lake Manitou during June 1985.

becoming extremely turbid with inorganic silt during periods of spring runoff delivered via Graham Ditch. Core E was selected to indicate the importance of this contributer to Lake Manitou. Core W was taken as a pseudo-control, in that it was opposite Big Island and thus less susceptable to the silt loading directly. Being in the center of the lake it would serve as a site for integrating the water quality of the whole lake. While both cores were dated using 210-Pb and were analyzed for organic and inorganic content and phosphorus accumulation, only Core E was analyzed for invertebrate remains. All cores were collected in two-meter-long plexiglass tubes attached to a piston corer. Each core was sectioned in 1-cm intervals, and sediment materials from each level were placed in plastic bags and frozen for transport to Florida. Analyses were performed in my laboratory at the University of Florida.

The paleolimnological research was undertaken to determine if Lake Manitou has become progressively more eutrophic in the past 100 years, and if so, has there been an acceleration in the process recently that can be related to known human activity in the watershed. The study concentrated on four parameters: 1) 210-Pb dating of sediment cores, 2) changes in the deposition of inorganic and organic sediment fractions, and 3) changes in the species composition and accumulation rates of major benthic invertebrate groups living on the lake bottom. The 210-Pb analyses were essential for establishing a time stratigraphy for each core. Inorganic and organic sediment fractions and their rates of annual accumulation on the bottom provide valuable information on watershed erosion and lake productivity, respectively. As phosphorus is the most likely limiting nutrient in

Lake Manitou, changes in the deposition rate of this most important nutrient for lake eutrophication reflect both the general history of eutrophication of the lake as well as alterations in the phosphorus input to the lake from the watershed.

All paleolimnological data in this report are presented in a standard format that may be unfamiliar to the reader. On all figures, the vertical axis denotes time as a function of depth in the core. The most recently deposited material (1985) would be at the top of the core labelled "0", which represents the water column/sediment boundary. Progressively older sediments are thus at depth in the core. Accumulation rates for individual parameters are given as the amount of a given parameter deposited per square centimeter of lake bottom per year (# or $mg/cm^2/yr$). Such accumulation rates have been calculated for that section of the core that is within the limits of the 210-Pb dating procedure and are always accompanied by the calculated chronological dates for the core profile. The horizontal scale on all figures denotes changing concentrations or number of a particular paleolimnological parameter.

<u>210-Pb Dating</u>. 210-Pb is a naturally occurring radionuclide in the uranium-238 series and has a half-life of 22.26 years. It is the accepted technique for dating lacustrine sediments deposited within the past 120 years. Eleven stratigraphic samples for Core E and twelve from Core W were analyzed for 210-Pb using the technique of Eakins and Morrison (1978) and an alpha-spectrometer as a detector.

The age/depth relationships for both cores are given in Figure 4. From 1860 to 1900, the sedimentation rate in the eastern basin (Core E) was 9.8 years/cm of sediment thickness, while that of the western

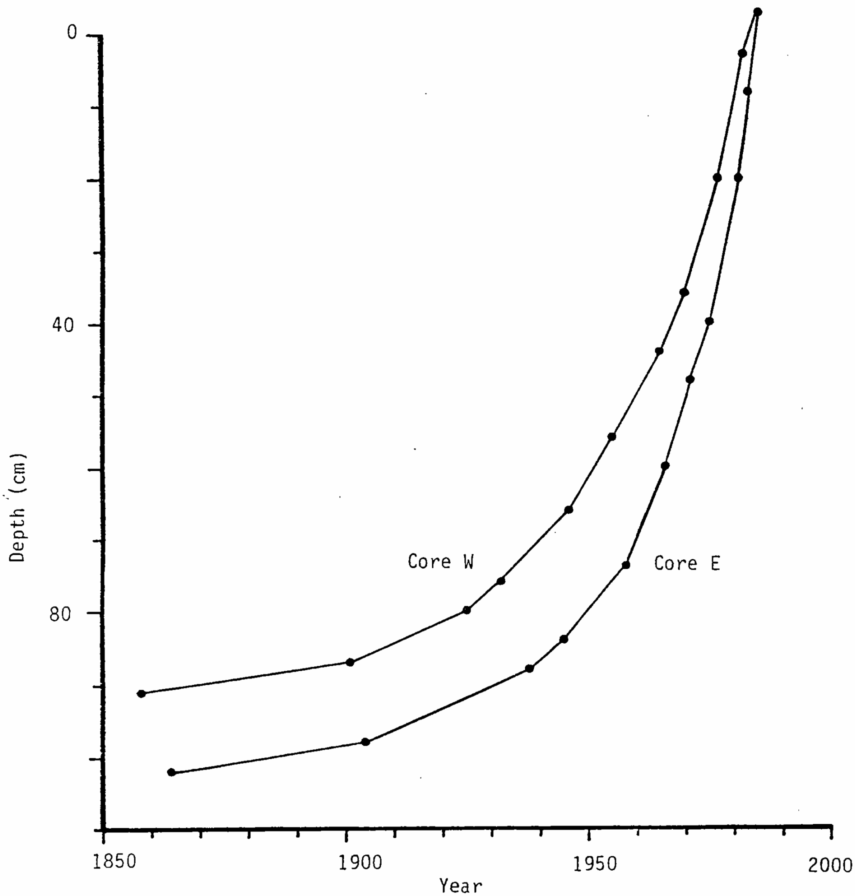

Figure 4. Depth/year profiles for cores from the western and eastern basins of Lake Manitou.

basin (Core W) was 10 percent lower at 10.8 years/cm. During the next 30 years (1900-1920), sedimentation was comparable in both basins (3.3 years/cm). This rate was, however, over three times greater than the previous period. Sedimentation remained constant in the eastern basin (3.3 years/cm) from 1920-1940, while that of the western basin progressively increased throughout the period (2.53-1.50 years/cm). For the first time, sedimentation rates were higher in the western basin than in the eastern basin (30 percent in the 1920´s and 120 percent in the 1930´s).

Sedimentation increased progressively in both basins during the period 1940-1960, with the rate of the western basin again being greater than in the eastern basin (39 percent in 1940´s and 26 percent in 1950´s). Sedimentation rates for the western basin were 1.14 and .82 years/cm during the 1940´s and 1950´s, respectively, while those for the eastern basin were 1.59 and 1.04 years/cm. It is interesting to note that the 120 percent difference in the sedimentation rates between the two basins noted for the 1930´s progressively declined during the next two decades so that by 1960 the western basin rate was only 26 percent greater than that of the eastern basin.

Since 1960, however, the pattern delineated for the period 1920-1960 has been reversed so that sedimentation has been greater in the eastern than in the western basin. Sedimentation in the eastern basin was 54 percent greater (.44 versus .68 years/cm) during the 1960´s, remained relatively constant (53 percent greater) during the 1970´s (.30 versus .46 years/cm), and increased further (61 percent greater) post 1980 (.21 versus .34 years/cm).

In summary, on the basis of bulk sedimentation rates, four major periods of sedimentation can be identified. The first period (1860-

1900) was characterized by only slightly greater sedimentation rates being recorded in the eastern basin (10 percent). The second period (1900-1920) was one of increasing but comparable sedimentation rates in both basins. During the third period (1920-1960), sedimentation was clearly greater in the western than in the eastern basin although increasing rates in the eastern basin gradually reduced the disparity between basins. The fourth and final period (1960-1985) was characterized by greater sedimentation rates in the eastern basin. If 1860 sedimentation rates are considered baseline for each basin, then the post 1980 rates for the eastern basin are 47 times greater than baseline, while those of the western basin are 32 times greater than baseline. Sedimentation rates began to increase in both basins after 1900, and with the exception of 1900-1930 when rates remained constant in the eastern basin, have increased progressively since then.

Organic and Inorganic Sediment Fractions. Depth profiles for percent water and organic matter are presented for cores from the western and eastern basins in Figures 5 and 6, respectively. Percent water is a measure of the degree of sediment compaction, and percent organic matter is a measure of material deposited from algal and macrophyte production in the lake proper as well as that organic fraction washed into the basin from the watershed. The remainder of the sediment fraction at any core level is considered inorganic and represents the delivery of erosion products from the watershed.

Core W from the western basin (Figure 5) was always greater than 77 percent water. Although rates did display some stratigraphic variations below 15 cm, they averaged approximately 80 percent water. The percent water increased progressively from 15 cm to the surface of the core reflecting the soupy nature of the uppermost sediments. The

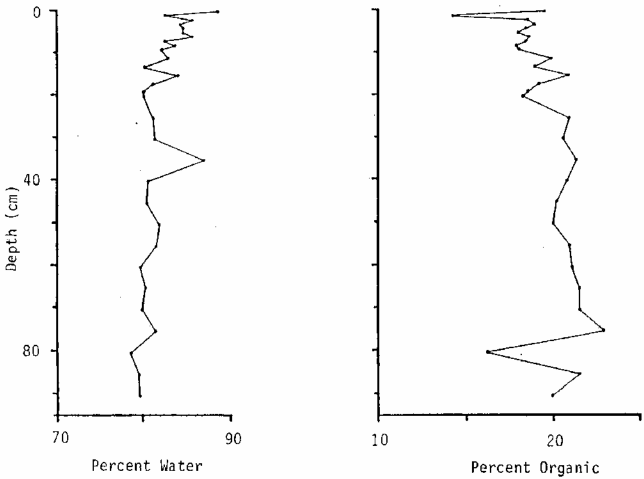

Figure 5. Percent water and organic content for select levels of the sediment core from the western basin of Lake Manitou.

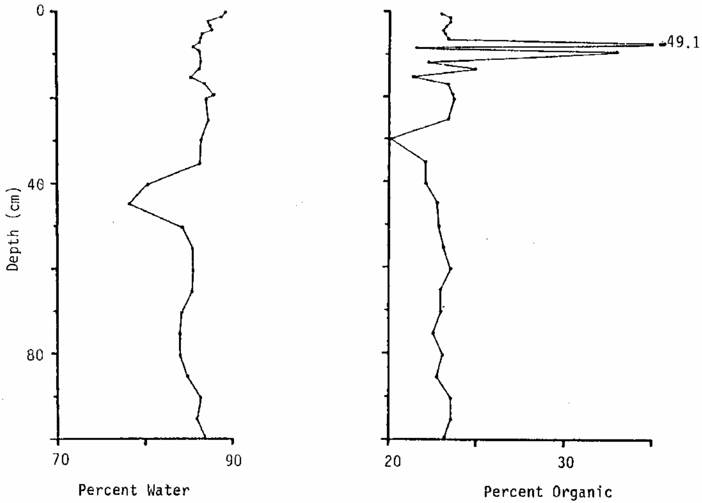

Figure 6. Percent water and organic content for select levels of the sediment core from the eastern basin of Lake Manitou.

organic content of this core was greatest at the bottom and decreased progressively to the surface. At no time did organic content exceed 25 percent of core weight.

Water content of the core from the eastern basin (Core E) averaged approximately 87 percent (Figure 6) and was consistently higher than values recorded for the western basin. Sediments of the eastern basin have thus been less compact ("soupier") than those of the western basin. With the exception of a short term peak recorded at 10 cm, organic content of Core E averaged approximately 23 percent and thus was comparable to that recorded from Core W.

Annual accumulation rates ($g/cm^2/yr$) for total dry sediment and its organic and inorganic fractions in the western basin of Lake Manitou are presented in Figure 7. Dry sediment accumulation rates have increased progressively since at least 1880 with the greatest incremental increase taking place during the mid-1970's. Values since that time appear to have decreased somewhat. Organic matter accumulation rates increased slowly from 1880 until the mid-1970's after which they have declined slightly. Examination of the inorganic sediment profile shows clearly that this sediment fraction is the dominant contributor to the previously described pattern of total dry sediment accumulation rates. The sedimentation rate of inorganic sediment increased from 1880 until 1950 when the rate of increase accelerated from .135 to .275 $g/cm^2/yr$. Values remained at this level until the 1970's when peak inorganic sediment accumulation rates of .485 $g/cm^2/yr$ were recorded. There has been a decrease in sedimentation rates since that time to approximate values recorded in the 1950-1970 period.

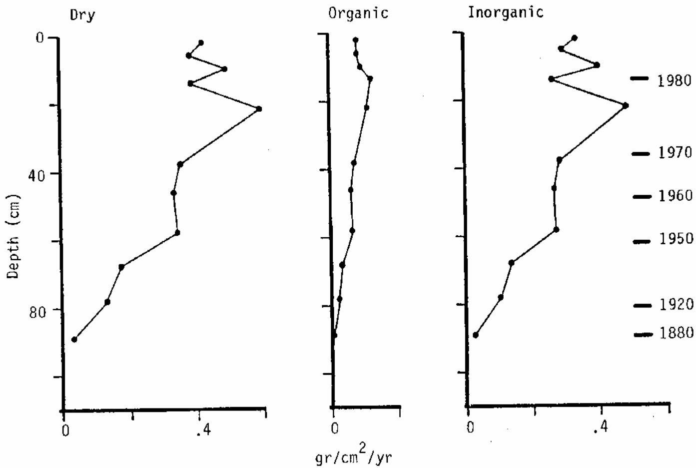

Figure 7. Annual accumulation rates of total dry, organic and inorganic sediment fractions in the core from the western basin of Lake Manitou.

Profiles for the eastern basin are similar to those described above for the western basin (Figure 8). Total dry sediment accumulation rates in this basin increased progressively from 1880 until the early 1970's when values plateaued and remained constant for the entire decade. Beginning in the early 1980's total sediment accumulation rates increased sharply to reach maximum core values of .76 $g/cm^2/yr$. Values in 1983-1985 were somewhat lower than this peak but still approximately 25 percent higher than recorded in the 1970's.

Organic matter accumulation rates increased slowly but progressively from .01 to .12 $g/cm^2/yr$ between 1880 and 1980 and increased slightly post 1980. As described for the western basin, the inorganic sediment fraction clearly controls the stratigraphic profile for the accumulation rate of total dry sediment. It appears that inorganic sedimentation increased sharply during the mid-1970's but has decreased somewhat since then.

Together, the cores from the eastern and western basins give a clear picture of the history of sedimentation in Lake Manitou. It is reasonable to assume in a eutrophic lake such as Manitou that the organic matter that is being deposited on the lake bottom is produced within the lake proper and that the accumulation rate of this parameter is directly proportional to the rate of production (trophic state). Stratigraphic changes, then, should reflect historical variations in the trophic state of the lake for the period covered by the core.

Organic matter accumulation rates in Lake Manitou in 1880 were approximately .01 $g/cm^2/yr$. Values for Lake Maxinkuckee in 1880, when we have strong evidence that it was oligotrophic-mesotrophic (Crisman 1986b), were 50 percent lower (.05 $g/cm^2/yr$). A value of .09 $g/cm^2/yr$

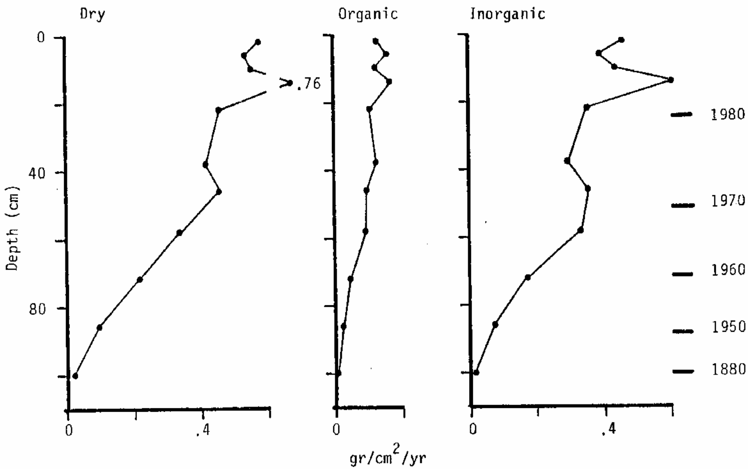

Figure 8. Annual accumulation rates of total dry, organic and inorganic sediment fractions in the core from eastern basin of Lake Manitou.

has been recorded in Lake Maxinkuckee only since 1980 when we know that the trophic state was at the boundary between mesotrophic and eutrophic conditions. Based on such evidence, it is suggested that Lake Manitou was highly eutrophic as early as 1880 when human impact on the system was minimal. Since that time the lake has continued to become progressively more eutrohic with peak organic accumulation values peaking in approximately 1980. There is slight evidence that the condition of the lake may have stabilized or slightly improved since then.

Inorganic accumulation rates are ultimately a direct result of the delivery of erosional products from the watershed. Accumulation rates were .02 $g/cm^2/yr$ in both basins of Lake Manitou in 1880, while they were .04 $g/cm^2/yr$ in Lake Maxinkuckee for the same date (Crisman 1986b). Such values are considered baseline values of erosion from relatively undisturbed watersheds of northern Indiana prior to extensive land clearance by European settlers. Inorganic accumulation rates increased slowly but progressively from 1880 until 1950 when they increased sharply. Values remained at constant but high levels until the past ten years when they increased to the peak values recorded for the lake. A core maximum of .48 $g/cm^2/yr$ was recorded in the western basin in 1977, while a maximum of .61 $g/cm^2/yr$ was recorded in the eastern basin in 1982. Such a minor discrepancy between the two cores regarding the date of maximum delivery of inorganic material is not surprising given the fact that the eastern basin sedimentation rate is a reflection principally of the contribution of Graham Ditch, while the western basin integrates the whole watershed including the contribution of Rain Creek. In addition, as will be discussed later in this report, the 1977 peak for the western basin is likely to have been strongly influenced by the canal dredging that took place along the southwestern shore of the lake during the same period. Finally, data from both basins suggest that the annual accumulation rates of inorganic material in the lake for the past 2-3 years have declined slightly from peak values recorded during the previous five year period. In spite of this decline, accumulation rates in Lake Manitou are still approximately ten times higher than the maximum delivery rate of inorganic material to Lake Maxinkuckee (Crisman 1986b).

Phosphorus. Phosphorus concentrations were determined according to the ascorbic acid colorimetric method (APHA 1980) using the filtrate collected from the HCl digestion technique of Andersen (1976). All analyses utilized 2 cc of sediment from each core level examined. Phosphorus data have been expressed relative to dry weight, organic weight, and inorganic weight of sediment in two ways. The first way (Figures 9 and 10) was to express phosphorus on a per gram basis for each sediment fraction, while the second way (Figures 11 and 12) took the calculations derived from the per gram basis and converted these to annual accumulation rates. Rather than discuss each plot individually, the following discussion will concentrate on delineating the general trends common to the database.

Phosphorus accumulation rates in both basins displayed similar historical patterns. Baseline values for the pre-1900 period were approximately .02 $g/cm^2/yr$ and were the lowest values recorded for both cores. Values gradually increased for the next 70 years when accumulation rates of this important nutrient increased to peak in the late 1950's and early 1960's. Although this peak period was of secondary importance compared to that displayed later in both cores

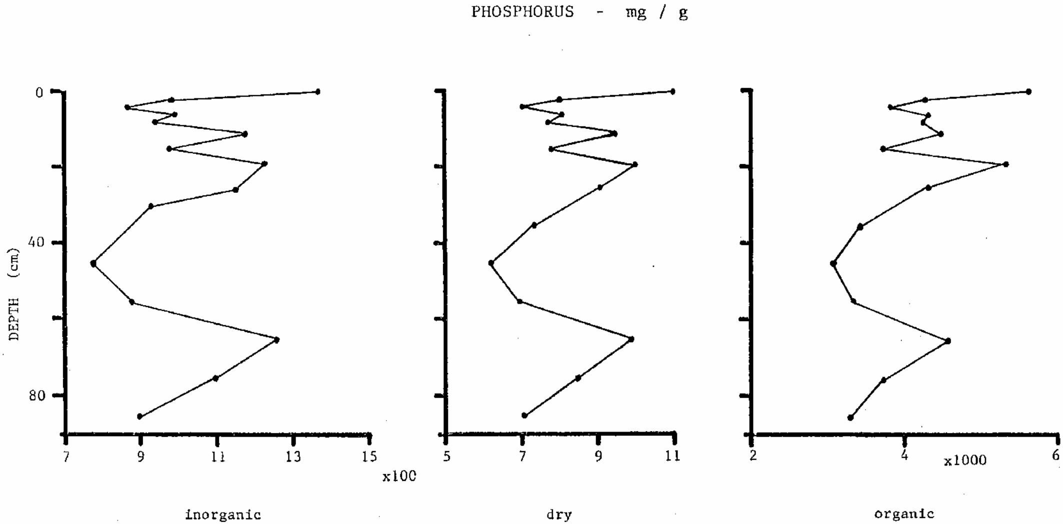

Figure 9. Phosphorus concentration expressed as mg/gr of inorganic, total dry and organic sediment fractions for the core from the western basin of Lake Manitou.

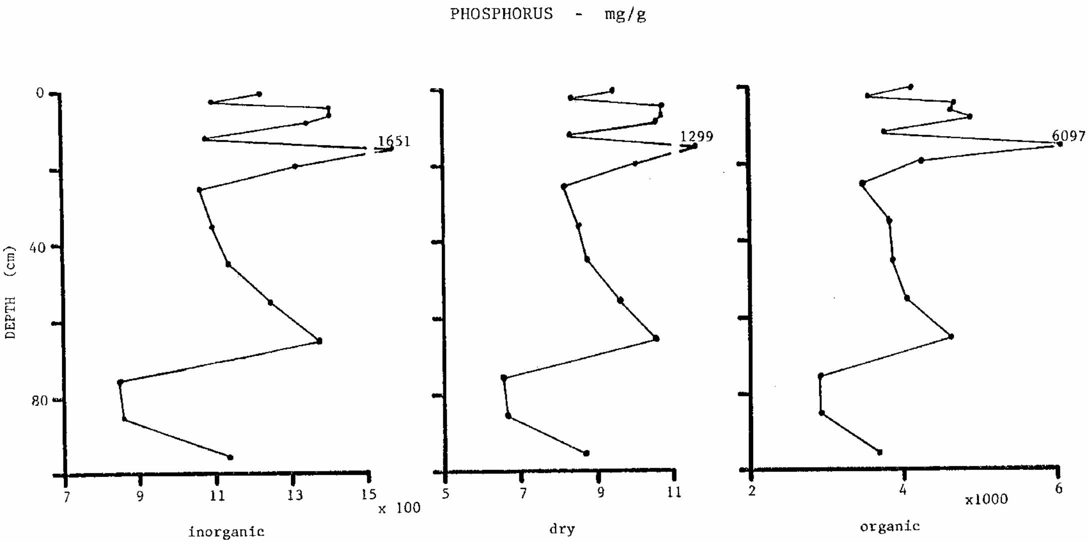

Figure 10. Phosphorus concentrations expressed as mg/gr of inorganic, total dry and organic sediment fractions for the core from the eastern basin of Lake Manitou.

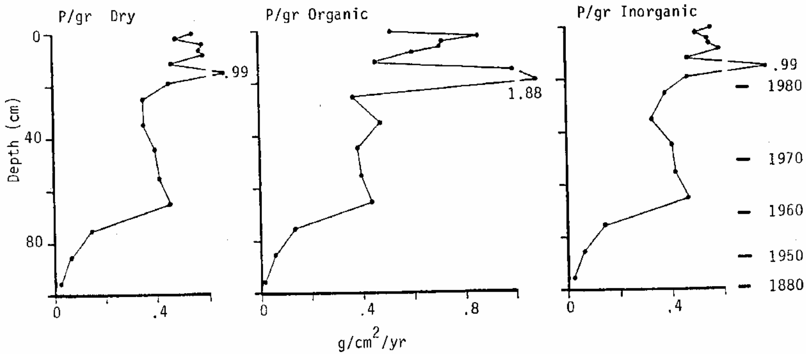

Figure 12. Annual accumulations rates (gr/cm^2/yr) of phosphorus expressed on a per gram basis for dry, organic and inorganic sediment fractions from the core of the eastern basin of Lake Manitou.

during the 1980's, it was more pronounced in the eastern basin (.45 g/cm^2/yr) than in the western basin (.24 g/cm^2/yr). Following this peak period, phosphorus accumulation rates remained relatively steady in the western basin until the mid-1970's and even declined slightly in the eastern throughout the 1970's.

Phosphorus accumulation rates in the western basin peaked in approximately 1977 and were the highest values recorded in the core from this basin. This peak corresponds with the time of maximum accumulation of inorganic sediment in this basin (Figure 7). As will be discussed later, this was a period of dredging for a housing development on the southwestern shore of the lake, and it is suggested that much of the inorganic material deposited in the lake during this period was related to this activity.

Peak phosphorus accumulation rates in the eastern basin occurred in 1981. Values during this year were approximately double the highest value of earlier periods. Although maximum core values for the western basin were recorded in 1977, the core of this basin did show a major peak also during 1981. Values recorded during this period were the second highest of the entire core. As was clearly evident regarding the 1977 peak in the western basin, the 1981 peaks in both basins corresponded closely with a peak in the input of inorganic sediment presumably exported from the watershed. Following the 1981 peak phosphorus values declined somewhat for the next 2-3 years but recently have begun to climb again to levels approaching the 1981 peak period.

<u>Benthic Invertebrates</u>. As noted previously, benthic invertebrates, especially chironomid midges, are good biological indicators of general lake productivity (degree of eutrophication) as

well as the concentration of oxygen in the lower levels (hypolimnion) of the water column. All past studies at Lake Manitou have reported a major reduction in the oxygen level of the lower water column during mid and late summer. Anoxic conditions have been reported during most summers. The failure of walleye stockings is quite likely attributed in part to the lack of high oxygen levels during summer in the lower colder segments of the water column.

Benthic invertebrate subfossil remains were examined for multiple levels of the eastern basin core representing a time chronology from the present to pre-1900. I was particularly interested in determining: 1) if the lake has always developed profundal anoxia during summer or whether such conditions are the direct result of human activities, and 2) if major changes have taken place in the abundance and taxonomic composition of the benthic invertebrate community as a result of lake eutrophication.

For each core level, 2 cc of sediment were cooked in 10 percent KOH for 15 minutes after which the residue was filtered through an 80 um screen. The entire fraction retained by the screen was examined under a microscope, and each subfossil remain was isolated individually from the sediment matrix with an Eppendorf pipet and placed on a glass microscope slide containing a drop of silicon oil. After all individuals were thus isolated, a coverslip was added to the slide, and this permanent mount was examined under a microscope at 200x for detailed taxonomic work.

The major invertebrate groups identified in the present study were: bryozoans, Chaoborus, and chironomid midges. Bryozoans are colonial jelly-like animals that attach to aquatic weeds, docks, and other hard objects and filter water to feed on algae. They are represented in the subfossil record by their resting eggs called statoblasts. Crisman et al. (1986) related the abundance of bryozoan statoblasts in lake sediments to known environmental variables including lake water chemistry, degree of eutrophication, and extent of weed beds and noted that bryozoan abundance in sediments is positively correlated with the extent of weed beds in a lake as well as the general abundance of algae in the water column.

Chaoborus is a large invertebrate predator that lives as a benthic invertebrate during the day but swims to the upper portions of the water column at night to prey on microcrustaceans and rotifers. It is represented in the sedimentary record by its mandibles. This organism is of particular interest in the present study because in lakes that develop severe oxygen depletion in deeper waters during summer, whether by progressive eutrophication or some one-time catastrophic event, Chaoborus is able to still retreat to the dark cool bottom waters in order to avoid predation by fish, while fish can not enter this area. The enhancement of Chaoborus subfossils from the sedimentary record thus can provide a valuable chronological marker for the initation of summertime anoxia in deep water. Crisman and Crisman (1987) have provided the first quantitative interpretation of chaoborid subfossils in lake sediments.

The third and final benthic invertebrate group examined in the present study is chironomid midges. Midges are represented in the sedimentary record by their chitinous head capsules. As most of the taxonomy of this group is based on features of the head capsule that are preserved upon death of the organism, a great deal of information can be obtained from the sedimentary record. Midges are used by the United States Environmental Protection Agency and state environmental regulatory agenices as the preferred biological indicator organism for defining both the degree of lake productivity (eutrophication) and mid summer oxygen levels in the deeper portions of a lake's water column (hypolimnion). A detailed treatment of the use of all three invertebrate groups discussed above in applied ecological investigations is provided in Crisman (1987).

Accumulation rates for Nitella, bryozoans, Chaoborus, and total chironomid midges are presented in Figure 13. Nitella is a macroalga characteristic of hard water lakes and is represented in the sediment record by its reproductive structures. This plant is anchored to the bottom sediment and is useful for estimating the extent of submergent macrophytes in a lake. Both Nitella and submergent vascular macrophytes are anchored to the substrate and are limited by a similar suite of environmental variables including light penetration through the water column. The abundance of Nitella remains is considered to be directly related to water column clarity and nutrient availability. By extension, historical patterns in the abundance of Nitella should parallel those of the submergent vascular macrophyte community.

Prior to the mid-1950's, Nitella accumulation rates were low but constant at less than $1/cm^2/yr$ suggesting a reasonably stable macrophyte community. Values displayed a brief spike in the late 1950's and began a rapid progressive increase in the late 1960's to peak at maximum core values of $21/cm^2/yr$ in approximately 1978. Since that time, Nitella accumulation rates have declined somewhat, but have displayed secondary peaks in 1981 and 1982. It is suggested that the trend established for this macroalga is a reasonable approximation of

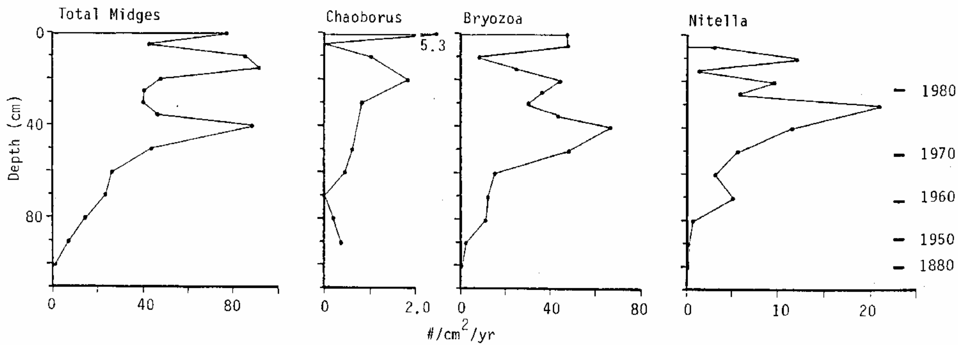

Figure 13. Annual accumulation rates of total midges, Chaoborus, bryozoa and Nitella in the core from the eastern basin of Lake Manitou. Please note scale change for Chaoborus and Nitella.

that of the total vascular macrophyte community in the lake. It is interesting to note that the 1978 peak in macrophytes is coincident with increased delivery of inorganic sediment into the lake and the associated increase in phosphorus accumulation rates. A similar relationship can be established to explain the 1981-1982 peak in Nitella.

Further support for the hypothesized trend in macrophyte abundance based on Nitella subfossils is provided by bryozoans statoblasts. Bryozoan stratigraphy is remarkably similar to that of Nitella and suggests that the macrophyte community only began to expand markedly after the mid-1960's and reached its peak in 1978. Although the extent of the weed beds declined somewhat since that time, two additional secondary peaks in weed abundance were noted in the 1980's.

The cause of the post 1980 macrophyte decline is not readily discernible from the present database. According to Jim Ewen (personal communication) the lake was treated between 1980 and 1984 with Diquat, Copper Sulphate, and Aquathol to reduce the extent of macrophytes. Although detailed records are lacking, he indicated that approximately two-thirds of the shoreline was treated annually with treatment taking place in early spring during April. Although it appears that such a management practice was effective at reducing weed beds, the importance of natural regulating factors including the severe winters of the period can not be adequately assessed.

Chaoborus appeared in the Lake Manitou core in approximately 1950 but was not consistently encountered in the sediment record until approximately 1966. From 1966 until 1977 accumulation rates of this invertebrate predator increased slowly but progressively. As noted previously for Nitella and bryozoans, Chaoborus peaked in 1981, but this peak was of secondary importance compared to the core maximum for this organism (.53/cm^2/yr) recorded in the most recently deposited sediments of the lake. The chaoborid data suggest that the lake may not have consistently developed anoxic conditions in deep water (hypolimnion) during midsummer until the mid-1960's. The fact that chaoborid accumulation rates are relatively high through the lake history covered by the core are also suggestive that oxygen concentrations have always been greatly reduced during mid to late summer, but as previously stated, this condition has likely worsened since the mid 1960's. For comparison, Lake Maxinkuckee, a lake of lower trophic state than Lake Manitou, has extremely low populations of Chaoborus in spite of its greater depth. In the core from the latter lake, chaoborids were encountered in only one core level and then only at an abundance of .05/cm^2/yr, ten times lower than the maximum recorded in the Manitou core.

Total midge accumulation rates were approximately 1/cm^2/yr pre-1900 and approximated values recorded for Lake Maxinkuckee for the same period (Crisman 1986b). Values then progressively increased for the next seventy years and peaked in approximately 1975. Accumulation rates declined somewhat during the next five years, but increased to reach peak core values in 1981. There is some evidence for a slight lowering of rates during the past four years. Accumulation rates for Lake Manitou for the time covered by the core were between 10 and 30 times greater than recorded even during the post productive period at Lake Maxinkuckee (Crisman 1986b). Such a distinctive difference between these two lakes demonstrates clearly the highly eutrophic nature of Lake Manitou.

Four major midge groups are represented in the Lake Manitou core (Figure 14). The chironomid assemblage of Lake Manitou has always been dominated by taxa in the Chironomini. The percentage dominance of this group ranged from 34 to 86 percent of the total assemblage abundance. The principal subdominant group, Tanypodinae, comprised between 14 and 53 percent of total abundance. Although both displayed some stratigraphic variations in their relative dominance, no clearly discernible patterns were apparent. It is important to note that these two midge groups are usually dominant in mesotrophic to eutrophic temperate lakes. Two groups that reach their greatest dominance in oligotrophic and mesotrophic lakes, Orthocladinae and Tanytarsini, were the third and fourth most important midge groups in Lake Manitou, respectively. Orthoclads never made up more than 18 percent of total abundance and displayed little discernible stratigraphic trend. Tanytarsini was the only midge group to display a clear stratigraphic pattern in percentage abundance. This group is normally the principal faunal element in oligotrophic temperate lakes and is normally progressively replaced by Chironomini and Tanypodinae with increasing eutrophication. While the Tanytarsini were consistently present in Lake Manitou before 1975, they occurred only sporadically after that date. The disappearance of this faunal group is further evidence of the fact that the lake has become progressively more eutrophic since 1975.

Accumulation rates for the four principal midge groups encountered in the Lake Manitou core are presented in Figure 15. The accumulation rates of the Chironomini increased progressively from

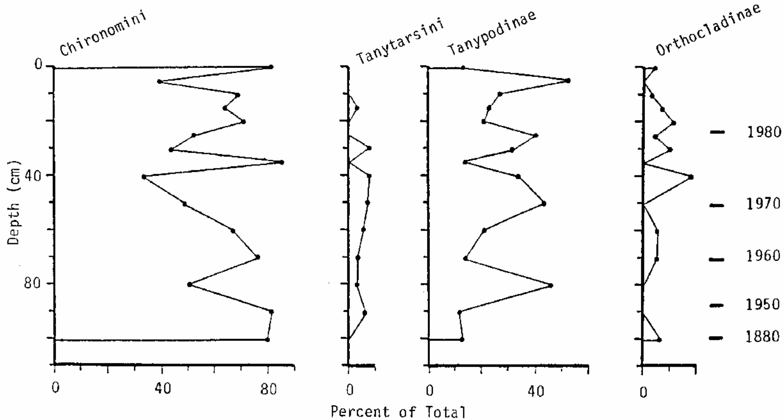

Figure 14. Percentage contribution of major midge groups to the total midge fauna of the core from the eastern basin of Lake Manitou.

1880 until approximately 1975, oscillated at somewhat lower levels until 1980, then reached peak core values during 1981. Values for 1981 represented a ten fold increase in the accumulation rates of 1880. Rates for the second most important group in Lake Manitou, Tanypodinae, displayed a historical trend similar to that of the Chironomini, but the magnitude of the change was much less pronounced. The accumulation rates for Orthocladinae remained relatively constant from 1880 until the mid-1970's when a short term peak was noted. Values since this time period have remained relatively constant, but at levels approximately two times greater than recorded during the pre-1975 period. The fourth and final midge group, Tanytarsini, displayed relatively constant abundance prior to a 1975 peak, but unlike the three other groups, was only sporadically found from 1975 to 1981 then disappeared from the lake. As stated earlier, the trends in this latter group are likely to most closely approximate the trophic state of the lake, with the total disappearance of this pollution sensitive group after the late 1970's being indicative of the accelerated pace of the eutrophication of the lake since this time.

Historical changes in the percentage dominance of individual taxa of midges in Lake Manitou are presented in Figure 16. The five most important genera throughout the lake's history have been: Chironomus, Dicrotendipes, Glyptotendipes, Polypedilum, and Ablabesmyia. The first three taxa are members of the Chironomini, while the fourth is a tanypod. All four taxa are common components in the benthic invertebrate fauna of eutrophic lakes. Four genera were only found in Lake Manitou prior to the early 1970's. These included:

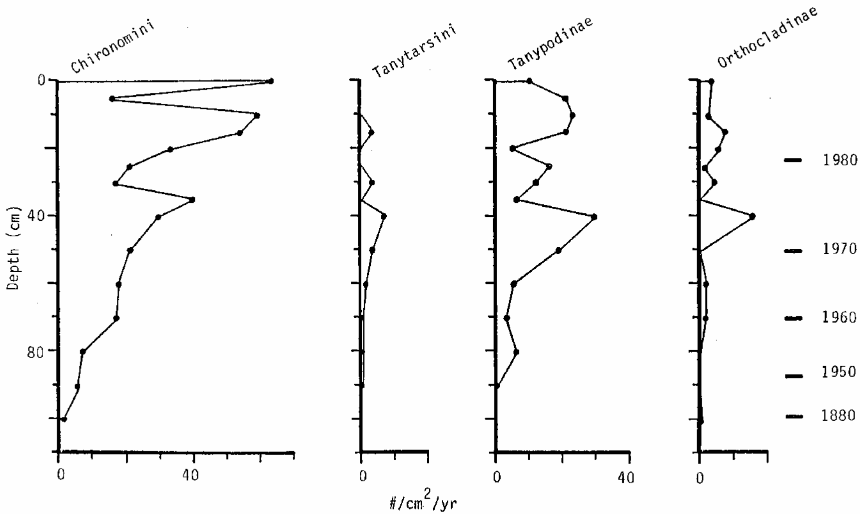

Figure 15. Annual accumulation rates of major midge groups in the core from the eastern basin of Lake Manitou.

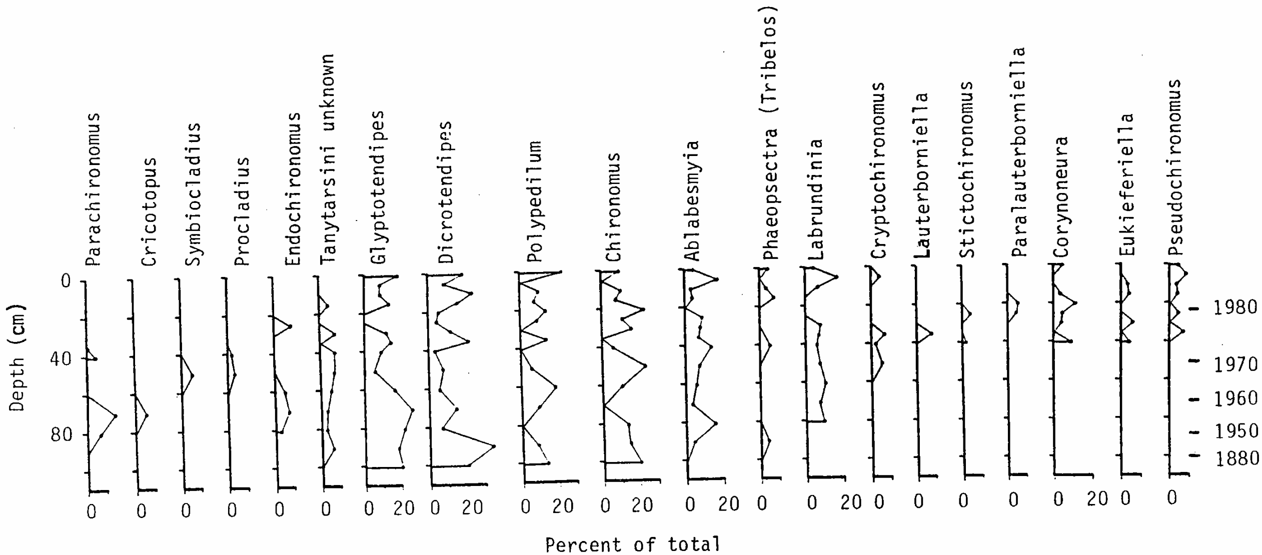

Figure 16. Percentage contribution of individual taxa to the total midge fauna of the core from the eastern basin of Lake Manitou.

Parachironomus, Cricotopus, Symbiocladius, and Procladius. Conversely, seven taxa were first encountered in sediments deposited after 1970: Cryptochironomus, Lauterborniella, Stictochironomus, Paralauterborniella, Corynoneura, Eukiefferiella, and Pseudochironomus. The remaining nine taxa identified displayed much broader historical distributions in Lake Manitou with most being present throughout the time period covered by the core. It appears that the major increase in the trophic state of Lake Manitou beginning in the mid-1970's had a pronounced impact on the taxonomic composition of the chironomid assemblage of the lake. Advancing eutrophication resulted in the elimination of four genera and their replacement by seven genera previously not recorded in the fauna during the prior century.

Accumulation rates for individual taxa encountered in the Lake Manitou core are presented in Figure 17. Examination of the data demonstrates clearly that during the progressive eutrophication of Lake Manitou individual taxa responded differentially to increasing lake fertility. The initial acceleration of phosphorus loading to the lake in the late 1960's and early 1970's was accompanied by increased abundance of Ablabesmyia, Chironomus, Labrundinia, Polypedilum, Glyptotendipes, Dicrotendipes, Tanytarsini, Eukiefferiella, Corynoneura, and Pseudochironomus. As eutrophication continued to increase in the late 1970's, it appears that the more pollution sensitive taxa including Tanytarsini, Stictochironomus, Lauterborniella, and Paralauterborniella were eventually eliminated from the invertebrate fauna. Among those taxa continuously present throughout the cultural eutrophication period, Cryptochironomus, Ablabesymia, and Corynoneura reached their maximum abundance during

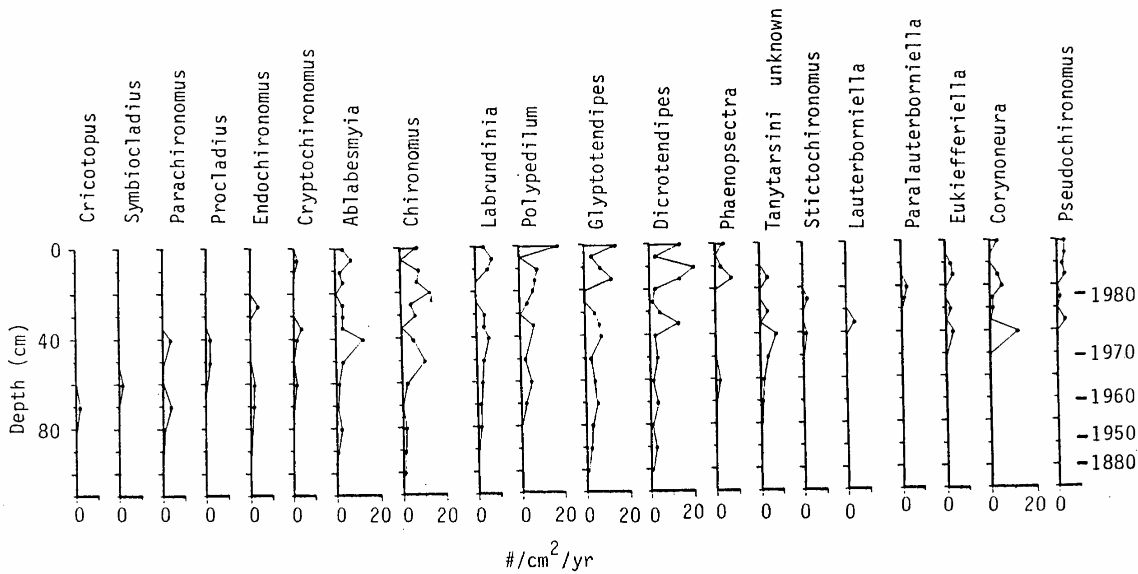

Figure 17. Annual accumulation rates of individual taxa in the core from the eastern basin of Lake Manitou.

the early phases of increasing lake fertility in the late 1960's and early 1970's. The post-1980 continued acceleration of eutrophication has witnessed the maximum abundance of Chironomus, Polypedilum, Glyptotendipes, Dicrotendipes, and Phaenopsectra. The dominance by these pollution tolerant taxa as well as the general reduction in the number of taxa present in the lake demonstrate that the cultural eutrophication of Lake Manitou has accelerated so rapidly since the late 1970's that the lake is most likely anoxic in its lower reaches throughout most of the summer. The biological changes and the pronounced increase in phosphorus accumulation rates since the mid 1970's when the ISBH collected data for their Indiana lake classification system have been sufficient to change the status of Lake Manitou from Group III into Group IV, the category of worst water quality in the state.

SUMMARY OF LAKE MANITOU TROPHIC HISTORY

As stated earlier in this report, the database for water quality in Lake Manitou is short. Prior to 1970, most of the monitoring was related to health oriented bacteriology. Even for the past fifteen years the monitoring has been sporadic, and many important limnological parameters have received little if any attention. Fortunately, the paleolimnological record is temporally complete for the past 100 years thus providing the opportunity for comparison with the monitoring data collected post 1957 as well as permitting extension of assessment of water quality back to 1880. The latter date was determined because of the limits of the 210-Pb dating procedure.

A clear picture of the history of water quality in Lake Manitou for the past 100 years has resulted from the two phase research approached described above. The historical interpretation for individual parameters analyzed is in total agreement. The trophic history of Lake Manitou can be divided into four distinct phases: I) Early Impact Baseline (1880-1900), II) Slow Progressive Eutrophication (1900-1970), III) Accelerated Eutrophication (1970-1980), and IV) Hypereutrophy (1980-Present).

Early Impact Baseline (1880-1900). The evidence indicates clearly that Lake Manitou was a fairly productive system as early as 1880. The Tanytarsini, a group characteristic of oligotrophic and mesotrophic lakes, made up less than 10 percent of the total midge fauna, while the system was clearly dominated by the Chironomini. In contrast, Lake Maxinkuckee, even during its most productive period, was characterized by at least 10 percent dominance by Tanytarsini. In addition, phosphorus accumulation rates were higher than recorded for the most productive period at Maxinkuckee. It is reasonable to assume that the baseline condition for Lake Manitou during the pre-1900 period was slight to moderate eutrophy.

Even during this early period, the sediments of Lake Manitou were highly inorganic. This is not surprising given the fact that there is an extremely large watershed to lake area (24:1). In contrast, the watershed area at Lake Maxinkuckee is only 2-3 times greater than the surface area of the lake. In spite of the much larger watershed at Manitou, both lakes displayed comparable accumulation rates for inorganic sediments during the 1880's. Such a comparison clearly demonstrates that the first 50 years of European colonization in the Manitou watershed did not appreciably affect the rate of delivery of erosion material to the lake. Finally, while the production of the lake was strongly influenced by aquatic macrophytes, the extent of the weed beds during the 1880-1900 period was likely only a fraction of what it is today.

Slow Progressive Eutrophication (1900-1970). Beginning shortly after the start of the present century, the productivity of Lake Manitou increased. The paleolimnological data indicate a slow but progressive increase in lake trophic state for the next 70 years. Erosion from the watershed as measured by inorganic sediment accumulation rates continued to accelerate throughout the period as did the loading of phosphorus to the system. The biological response to increased nutrient availability was increased productivity of all components rather than replacement of sensitive taxa. It is quite clear that the macrophyte (weed) beds continued to expand for the seventy year period as did the invertebrate communities that are associated with them. While it is likely that the open water algae also increased in abundance, their biomass increase was not sufficient to hinder the macrophytes by reducing light penetration in the water column. Given the shallow nature of the lake and the gradual expansion of macrophytes, it is clear that this period of lake history was controlled by the productivity of the weed community. For the first time, evidence was found for the reduction of oxygen in deep water during summer. Chaoborus, an invertebrate that migrates to oxygen depleted bottom waters to avoid predation by fish, was encountered for the first time in the sediments. Both the sporadic occurrence and the generally low numbers when found suggest that while summertime oxygen concentrations were reduced as a result of increasing eutrophication, such depletions were neither as severe nor as temporally extended as recorded later in the lake's history.

Accelerated Eutrophy (1970-1980). Accumulation rates of inorganic sediment in the western basin were higher than at any other time in the lake's history. In contast, inorganic deposition in the eastern basin remained at relatively steady levels until after 1980. The sharp rise in both alkalinity and calcium concentrations in the water column during the 1970's clearly indicates that erosion from the watershed was affecting water chemistry. As demonstrated for inorganic sediment, phosphorus concentrations increased sharply during the 1970's.

While earlier periods of lake history were characterized by a general increased productivity of all existing biological components, the rapid eutrophication of the 1970's experienced the first major species replacements. Four genera of midges considered sensitive to advancing pollution were eliminated during the 1970's and replaced by seven taxa from the less sensitive category. The abundance of Chaoborus increased markedly during the 1970's suggesting that oxygen depletion in deep waters during summer was becoming more severe. Monitoring data collected during the period clearly support this interpretation. The failure of the walleye stocking of 1977 is likely related to the severe hypolimnetic oxygen depletion.

Macrophytes expanded rapidly in reponse to the increased phosphorus loading to the lake and reached their maximum historical extent by the late 1970's. Again, it is clear that the growth of the weed beds was able to keep up with the loading of phosphorus so that the open water algal community was not able to increase markedly in importance and outcompete weeds. Support for this interpretation is provided by the fact that neither water clarity nor water column phosphorus concentations increased significantly during the 1970's in spite of the greatly accelerated loading of phosphorus to the lake system. The weed beds were clearly able to expand in response to increased phosphorus loading thereby acting as a kidney to retain this essential element before it could become available to algae in open water.

Hypereutrophy (1980-Present). Inorganic sediment accumulation rates declined somewhat in the western basin, while those in the eastern basin were the highest ever recorded in the lake. Phosphorus accumulation rates displayed a similar pattern. Based on data collected in the mid 1970´s, the ISBH assigned Lake Manitou to their category of second worst water quality (Group III). Even at this time, the eutrophy points assigned to Lake Manitou (48) defined the boundary between this category and that of worst water quality (Group IV). Given the greatly accelerated phosphorus loading to the lake evident in the late 1970´s and 1980´s as well as the biological changes that have taken place in the 1980´s, it is clear that Lake Manitou has slipped into the category of worst water quality (Group IV). Limnologists commonly refer to such lakes as hypereutrophic and consider them to represent the productivity endpoint in the eutrophication process.

The importance of macrophytes in Lake Manitou appears to have declined somewhat from the peak representation of the late 1970´s. This is somewhat alarming given the fact that phosphorus loading to the lake has continued to accelerate, and algal scums are common now along shorelines in summer. Two interrelated factors are likely responsible for increasing importance of planktonic algae in Lake Manitou. The first is related to the filtering kidney effect of the macrophyte beds to trap phosphorus. It is entirely possible that the weeds were operating at maximal efficiency during the 1970's relative to the phosphorus loadings of the period. With continued acceleration of phosphorus loading rates in the 1980's, macrophyte growth was not able to keep pace with phosphorus addition to the lake, increasing amounts of this essential nutrient released into the water column. Such enhanced water column phosphorus levels stimulated algal growth, and the resulting increased biomass in the water column reduced light penetration to weed beds below. Such shading reduced the growth and extent of macrophytes thereby further reducing the ability of this important plant community as a phosphorus filter. A reduction in the macrophyte "kidney" coupled with continued acceleration in phosphorus loading rates have further stimulated algal growth to the point that Lake Manitou is dangerously close to becoming algal dominated. Once this happens, the prospects for lake management/restoration diminish.

The second factor contributing to the slight shift in system dominance from macrophytes to algae has been the weed control practices initated in the 1980's. Chemical treatment of weed beds further reduces the ability of macrophytes to filter out phosphorus and promotes algal growth. As will be discussed later, weed control should be approached cautiously until phosphorus loading rates to the lake have been effectively reduced.

A number of other important biological changes have taken place in Lake Manitou since 1980. Although Chaoborus accumulation rates declined during the early 1980's, they have recently increased to maximum values recorded in the lake suggesting that the duration and extent of oxygen depletion in deep water have continued to increase. The total number of midge taxa encountered in the lake has been reduced, and pollution sensitive taxa have been eliminated. The most important change regards the Tanytarsini, which were infrequently found in the lake between 1975 and 1980 and totally eliminated from the fauna after 1981. Within the fish fauna, brown bullheads have increased in importance, and the gizzard shad population has demonstrated its resilience after the erradication program of the 1970's. On a positive note, the northern pike stocked in the lake in the early 1980's have established a breeding population, and carp, normally a management problem in highly productive lakes, has not increased in abundance in spite of the accelerated pace of recent eutrophication.

WATERSHED FACTORS FOR CULTURAL EUTROPHICATION

It is clear that while Lake Manitou was relatively productive prior to colonization by Europeans in the area, it has become progressively more eutrophic in recent years. Limnologists term such increased eutrophication as a result of human activity cultural eutrophication. The two most obvious factors contributing to the cultural eutrophication of Lake Manitou are residential development and agricultural practices.

Population data for Rochester and Rochester Township for the period 1850-1980 are given in Figure 18. From a population of 651 in 1860, Rochester grew progressively during the next 40 years to reach 3,421 inhabitants by 1900. The population remained reasonably constant at between 3,364 and 3,835 for the next 40 years. Between 1940 and 1950 the population of Rochester increased by 22 percent to 4,673. The population of the town has remained within 400 of this figure for the past 30 years.

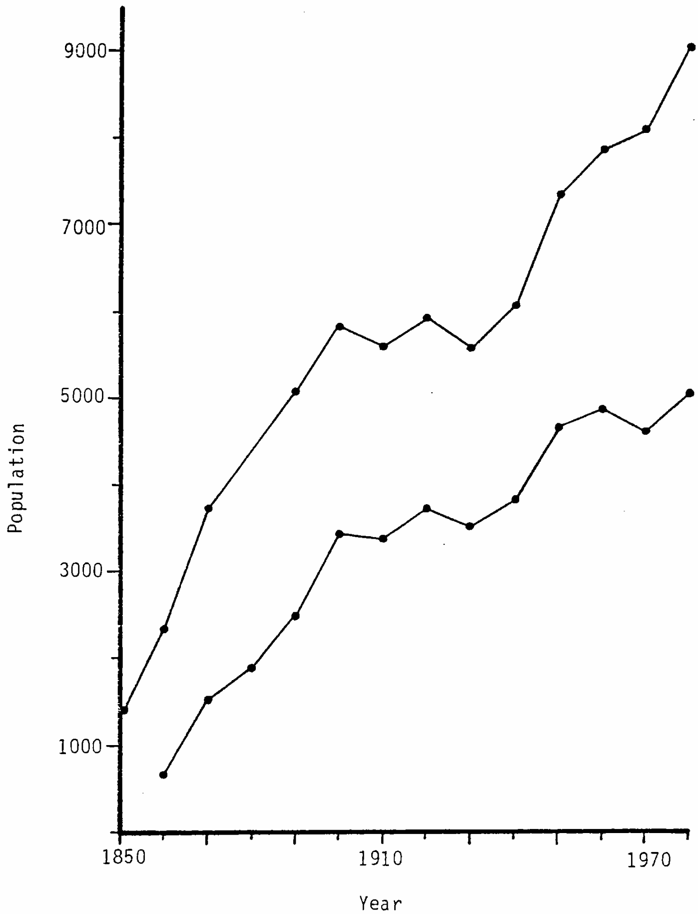

Figure 18. Population data for Rochester town (lower line) and combined Rochester town and unincorporated Rochester township (upper line) for the period 1850 - 1980.

A similar pattern has characterized the population history of the unincorporated areas of Rochester Township. Following a progressive increase from 1850 to 1900, the population remained relatively constant until after World War II when it increased by 20 percent between 1940 and 1950. Unlike the town of Rochester, however, the population of the unincorporated portion of Rochester Township has continued to climb post 1950. The 1980 population of Rochester was 32 percent greater than that recorded in 1940, while the population of the unincorporated township had increased by 80 percent in the same period. The decades of greatest population change for the latter were 1940 - 1950 (20 percent), 1960-1970 (16 percent) and 1970-1980 (15 percent).

The Indiana Department of Conservation constructed a bathymetric map for Lake Manitou in 1924 (Figure 19). In addition to delineating bottom contours for the lake, this map also provided a detailed assessment of the number of residences and businesses along the shore. Additonal information on residential development is obtainable from USGS topographic maps of the watershed. Two such map series exist for the Lake Manitou watershed. The first dated 1961 was based on information collected two years earlier, while the second was dated 1980 and was based on information collected during the previous three years.

A summary of residential construction activity for the period covered by the above maps is provided in Table 11. In 1924 there were 292 buildings along the shore of Lake Manitou. By 1962 this number had increased by 14.7 percent to 335, while during the next 18 years (1962-1980) a further 12.2 percent increase was noted. The 1980 figure

Figure 19. Indiana Department of Conservation 1924 map showing lake bathymetry and shoreline development.

TABLE 11. Major construction activity in the Lake Manitou watershed from 1924-1980.

I) SHORELINE BUILDINGS

YEAR	TOTAL	INCREASE	% INCREASE
1924	292		
1962	335	43	14.7
1980	376	41	12.2

II) TOTAL WATERSHED BUILDINGS

YEAR	TOTAL	INCREASE	% INCREASE
1924			
1962	805		
1980	997	192	23.8

of 376 buildings along the shore represented a 28.7 percent increase over the figure of 1924.

The total number of buildings in the whole watershed could only be assessed in 1962 and 1980. In the former year, 805 buildings were noted, but this number had increased by 192 to 997 for a 23.8 percent increase in 1980. Most of the construction between 1962 and 1980 was for residences along the southwest shore of the lake and in small development areas north of the mouth of Graham Ditch but away from the lake shoreline. In the same period that a 23.8 percent increase in residential development was noted in the watershed, the population of the area had increased by 33.4 percent.

The long term impact of increased residential development on Lake Manitou is through elevated phosphorus loading to the lake from improper or inefficient sewage disposal. None of the residential development documented for the Lake Manitou watershed since 1924 is connected to the Rochester sewer system. Rather, waste disposal is via individual private home systems. As early as 1957, the ISBH documented high bacterial contamination of Lake Manitou from improper sewage disposal and noted that in several cases disposal was simply into a 55 gallon drum buried in the yard. Bacterial contamination of the lake continued into the late 1960's when efforts by the ISBH and Fulton County Health Department to control the most serious violations of sewage disposal showed results. Controlling bacterial contamination should not be equated with controlling phosphorus loading to the lake from residences. Phosphorus leaching into water logged soils from drain fields may eventually enter the lake. The importance of this non-point source of pollution to total phosphorus loading is extremely difficult to measure directly. Rather, one can note how water quality changes relative to historical changes in watershed development.

While both phosphorus accumulation rates and human population display a general pattern of increasing values for the period 1880-1985, historical deviations from this overall trend do not coincide. Human population plateaued from 1900 to 1940, while phosphorus accumulation rates continued to increase progressively. Likewise, the 1981 phosphorus peak for the western basin and the 1977 and 1981 peaks for the eastern basin can not be explained by pulses in the human population. Most of the impact of human sewage on phosphorus loading rates should come from those residences built along the shore. By 1924, a total of 292 buildings ringed the shore of Lake Manitou, and this figure increased by only 29 percent over the next 56 years. Thus, 78 percent of the potential sources of residential phosphorus loading along the shoreline were present as early as 1924. Because most of the shoreline lots had been developed by this date, one would expect to have documented a pronounced increase in phosphorus loading rates coincident with this development. This was not apparent from the paleolimnological data as estimated 1924 phosphorus loading rates were only double estimates from the pre-1900 baseline condition for the lake. In addition, these 1924 rates were only 14 percent of the 1977 peak phosphorus accumulations in the western basin and only 8 percent of the 1981 peak in the eastern basin. While it can not be argued that human residential development along the shore was not a significant factor contributing to the early cultural eutrophication of Lake Manitou, other factors must be invoked to explain the recent acceleration in lake eutrophication.

Phosphorus accumulation rates in Lake Manitou (Figures 11 and 12) display a pattern that is most similar to historical variations in the annual accumulation rate of inorganic sediment in the lake basin (Figures 7 and 8). Phosphorus peaks coincide with peaks of inorganic sedimentation. The inorganic sediment is not generated within the lake basin proper but is delivered in direct proportion to the intensity of erosional processes within the watershed. Dredging and agricultural practices are likely the most important factors contributing to the increased deposition of inorganic material in Lake Manitou.

The 1980 USGS topographic map shows the presence of an artificial series of canals, hereafter referred to as finger canals, along the southwest shore of Lake Manitou (Figure 20). This feature was absent from the 1924 lake map (Figure 19). The 1962 USGS topographic map showed only the top arm of the canal system and half of the middle arm. The bottom arm and the remaining half of the middle arm of the canal system were present on the 1980 topographic map. Examination of the county records showed further that the area immediately north of the finger canal system was organized as a residential development in 1962 and that most of the area around the finger canals was organized in 1976.

Accumulation rates for inorganic sediment and phosphorus were greatest in the western basin of Lake Manitou during the late 1970's. In contrast, no peak was evident in the core from the eastern basin. As these two basins are separated by Big Island, the 1970's peak in the western basin likely reflects events taking place in that part of the watershed immediately adjacent to this section of the lake. It is suggested that dredging and construction activities along the southwest shore of the lake were the contributing factors for the

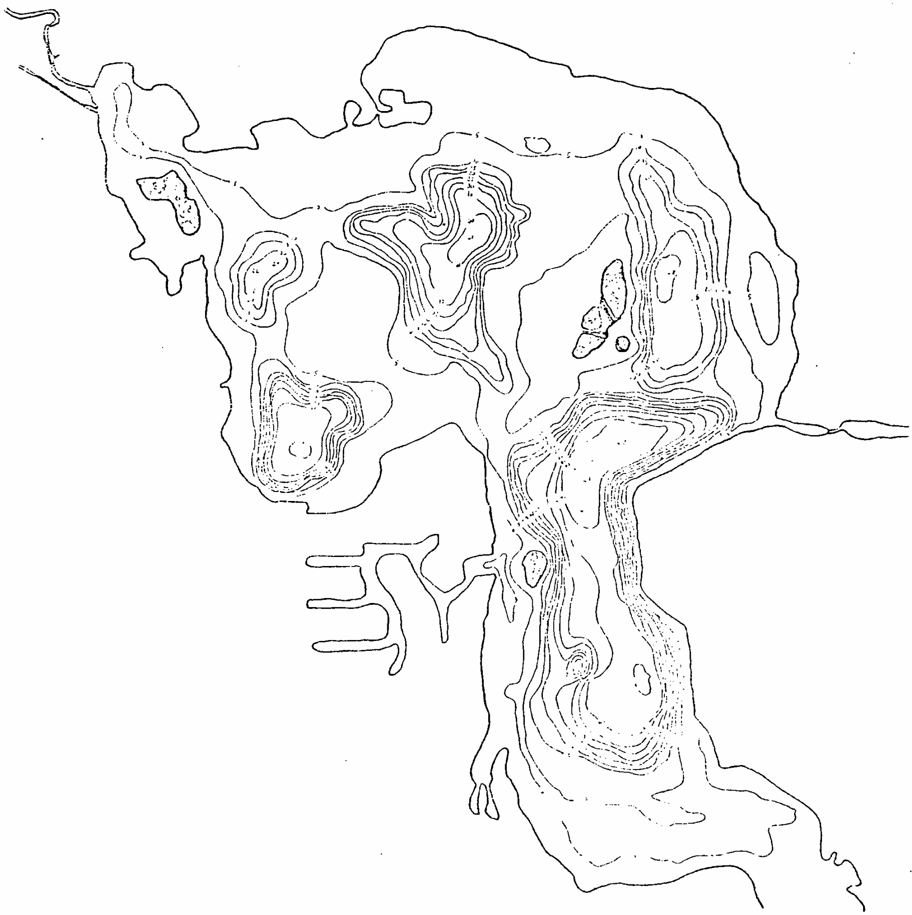

Figure 20. Shoreline of Lake Manitou 1980 based on USGS topographic map.

observed increase in both erosion material and phosphorus to the western basin in the 1970's. Earlier dredging for the first phases of canal construction are also likely responsible for the pronounced increase in both phosphorus and inorganic sediment in the western basin during the 1950's. Again, as with the later peak in the 1970's, the peak of the 1950's was not recorded in the eastern basin.

Agricultural practices are also likely to be responsible for much of the inorganic sediment entering Lake Manitou. Land disturbance for residential development can not explain the massive increase in the delivery of inorganic sediment to the lake basin after 1980. Both the western and eastern basins recorded pronounced peaks in sedimentation in 1981 with the peak for the eastern basin being the greatest recorded for the past 100 years. If the 1977 peak in sedimentation in the western basin is eliminated, then the 1981 peak in this basin is also the maximum for the core. It has been common during the 1980's for the water of Lake Manitou to become turbid in late spring as rains carry sediment from the agricultural fields of the watershed and deposit this material in the lake (David Herbst, personal communication). Although such periods of increased turbidity are of relatively short duration, it is obvious that they are contributing massive amounts of sediment to the lake annually.

Estimates of erosion from the Lake Manitou watershed are high. Dan Rosswurm of the Fulton County Soil and Water Conservation District in a Lake Manitou watershed status report in 1985 estimated that 55,875 tons of sediment are being eroded annually from the 3,725 acres of the watershed considered critically eroding cropland, and 21,032 tons are being removed from the 2,629 acres considered "somewhat" critically eroding cropland. Although not all of this 76,907 tons of inorganic sediment reaches the lake, even 30 percent of this figure would yield over 23,072 tons being added to the lake bottom per year.

As stated earlier, the watershed area draining into Lake Manitou is approximately 23.67 times larger than the lake itself (Figure 21). Given the fact that almost all of this watershed is agricultural, even moderate erosion rates would deliver large quanitities of inorganic sediment to the lake annually. Graham Ditch, which drains into Lake Manitou near the site of the core from the eastern basin, drains approximately 17.4 percent of the watershed area and appears as a natural stream on the 1833 plat map of the county. According to county records, the earliest dredging and channelization of this stream took place in 1902. The most recent manipulation of the system took place in 1984, when approximately four miles of the stream were dredged. Such channel dredging serves to increase water and sediment delivery to the lake.

The largest stream draining into Lake Manitou is Rain Creek. This stream drains approximately 25 square miles or 58.9 percent of the watershed area. Again, this section of the watershed is almost entirely agricultural. Two artificial ponds, Millark Millpond and Mt. Zion Millpond were constructed in the stream channel during the 1800's. Both ponds appear to be eutrophic and according to Dan Rosswurm, heavily sediment ladened. Sediment eroded from upstream fields has so filled the ponds that today little of the sediment eroded from upstream is retained by these two artificial ponds. Instead, the lake now serves increasingly as the settling basin for this erosion material. Because the Rain Creek watershed is 3.4 times larger than that of Graham Ditch, the recent high inorganic

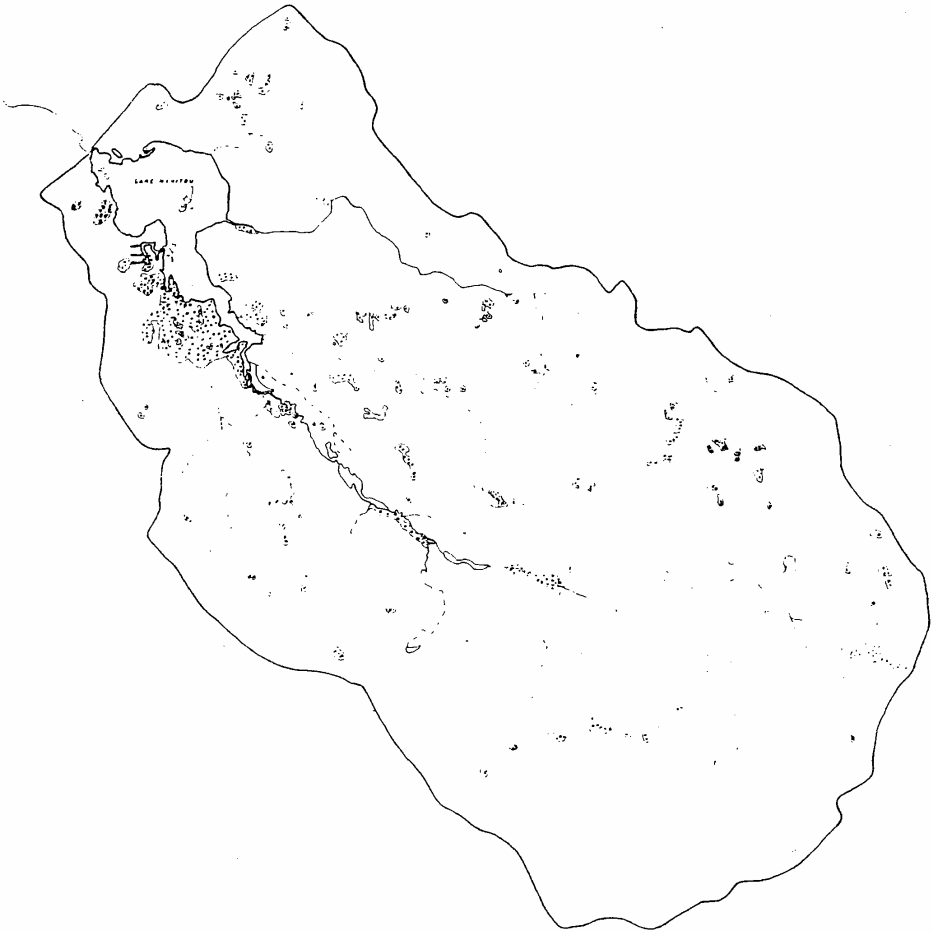

Figure 21. Lake Manitou and its watershed as calculated from USGS maps.

sedimentation rates documented for the latter system are likely to be but a fraction of those for the Rain Creek watershed.

Peak phosphorus delivery to Lake Manitou corresponded to times of increased inorganic sediment accumulation. These periods also coincided with documented changes in lake biology and degree of eutrophication. If residential development was the major source of phosphorus loading to Lake Manitou, then phosphorus accumulation rates should have reflected increasing human population in the area and associated sewage derived phosphorus loading and for the most part have been independent of inorganic sedimentation rates. The strikingly close agreement of phosphorus and inorganic sediment accumulation rates argues that the two parameters are derived from the same source. With the exception of the finger canal construction, residential development of the last forty years has been associated with a shift from seasonal and weekend to year-round residence in pre-existing houses. Thus, while new residences have been built in the watershed, properties along the shoreline were mostly developed by 1924. The inorganic sedimentation associated with construction of shoreline residences should have peaked prior to that time.

Cultural eutrophication of a lake is an additive process. A single event or practice should not be identified as the sole cause of the demise of a lake. In the case of Lake Manitou, it is obvious that both residential development and agricultural activities have contributed to the eutrophication of this lake. It is clear, however, that erosion has been responsible for the post-1980 acceleration of cultural eutrophication that necessitated the present investigation. With the exception of any future dredging for new construction, the contribution of residential phosphorus loading will be eliminated with the construction of the central sewer system that is ongoing. Given the fact that the erosion from the watershed is a much more significant phosphorus source than that from domestic sewage, Lake Manitou will not display any noticeable improvement in water quality until this nutrient source is also addressed and controlled. Even then, there will be a lag time between the elimination of all nutrient loading sources and lake improvement because of the shallow nature of the lake and the potential for resuspension of phosphorus from the lake bottom.

LAKE MANAGEMENT RECOMMENDATIONS

A list of management recommendations for Lake Manitou are provided in Table 12. These have been divided into three general categories: I) Reduction in delivery rate of watershed erosion material, II) Management of lake biology, and III) Institution of a public education program. These categories are ranked according to decreasing prioritization. Unless category I is completed first, then categories II and III become meaningless. The rationale for each recommendation is provided below according to the ordering scheme of Table 12. While the ordering of categories signifies decreasing order of priority, the ordering of specific recommendations within a category is not related to a priority scale.

I-A: Dredging of Mt. Zion Millpond and Millark Millpond. Based on conversations with Dan Rosswurm and my own personal observations, it is obvious that these two artificial ponds along the course of Rain Creek have so filled with sediment delivered by Rain Creek that their ability to function as a trap for inorganic sediment before it reaches

TABLE 12. Recommendations for Management of Lake Manitou.

I) Reduction in delivery rate of watershed erosion material.

   A. Dredging of Mt. Zion Millpond and Millark Millpond.

   B. Construction of sediment retention ponds of Graham Ditch, Rain Creek and Mastellar Ditch.

   C. Elimination of steep sided ditching that promotes bank erosion.

   D. Maintenance of green belts along streams.

   E. Prohibition of any further finger canal construction.

II) Management of Lake Biology.

   A. Protection and possible restoration of wetlands.

   B. Elimination of large scale weed control practices.

   C. Maintenance of DNR fish stocking program.

III) Institution of a public education program.

   A. Do not fertilize lawns.

   B. Do not remove shoreline vegetation.

   C. Do not dredge dock areas.

   D. Minimize wave generation by boating activities.

the lake has been seriously impaired. The correlation between watershed erosion of phosphorus and inorganic sediment and increased eutrophication is obvious by examining the condition of these ponds. If these ponds were non-existent, the material trapped by them and the resulting eutrophication effects would have been passed downstream to Lake Manitou proper. The Rain Creek watershed drains approximately 58.9 percent of the total watershed of Lake Manitou. As almost all of this area is devoted to agriculture, it is imperative that the sediment retention ability of these two ponds be restored. It is recommended that both be dredged to a depth that maximizes their water and hence sediment retention capacity. All dredged spoil material must be disposed at a distance sufficient to insure minimization of resedimentation in the ponds.

<u>I-B: Construction of sediment retention ponds at mouths of Graham Ditch, Rain Creek and Mastellar Ditch</u>. Graham Ditch drains approximately 17.4 percent of the Lake Manitou watershed. The historical significance of this ditch in the delivery of inorganic sediment from agricultural areas was clearly demonstrated by the current paleolimnological investigation. Since 1980 alone, this ditch has deposited 24 cm (9.44 inches) in the eastern basin of Lake Manitou and up to 16 cm (6.29 inches) in the western basin. This is in marked contrast to the deposition rate in both basins for the previous 80 year period of 74 cm (29.13 inches) and 73 cm (28.74 inches), respectively. The potential delivery rate of erosion material by this ditch was actually increased recently, when in 1984 large sections of the ditch were dredged to improve water flow. A sedimentation basin needs to be built near the mouth of this ditch to trap this large

sediment load before it enters the lake. It is suggested that this basin be built upstream from the marsh area at the ditch mouth and that the marsh be restored to sheet flow condition. Several designs can be followed for the sedimentation basin, but I prefer a broader shallower system planted with marsh vegetation to trap not only sediment but also associated phosphorus. A consulting engineer should be contacted for the best design alternatives for pond construction. Similar pond construction should be undertaken at the mouths of both Rain Creek and Mastellar Ditch. The latter stream, although draining a small portion of the total watershed, obviously carries a great sediment load given its general silted in appearance and rich vegetation. If properly designed, the sedimentation ponds envisioned for all three streams should have no adverse impact on drainage of agricultural land.

I-C: Elimination of steep sided ditching that promotes bank erosion. Jerry Bernard and Bill Beard of the United States Soil Conservation Service noted in a letter to Charles Gosset of their agency that their inspection of the Lake Manitou watershed in 1984 indicated several areas along streams that potentially or currently were subject to severe bank erosion. They noted that "reconstruction of Graham Ditch has resulted in ditch banks that are steep and may fail as the underlying sand and gravel outwash erodes. This could cause much sediment to accumulate in Lake Manitou along the north shore." Additionally, they found severe bank erosion at a poorly managed hog lot along Rain Creek (Robbins Taylor Ditch) in Miami County. My personal observations of the watershed in 1984 and 1985 support their findings. While it may not be feasible to reduce the bank slope of existing ditches and streams, any future stream dredging and "improvement" must eliminate steep bank construction. In the meantime, the watershed residents should regularly survey the lenghts of all streams and encourage the state and local land owners to repair any failing stream banks.

I-D: Maintenance of green belts along streams. Leaving vegetation zones along stream margins acts to trap sediment before it enters the stream. It is suggested that watershed residents work with local land owners and the Soil Conservation Service to develop a plan to best utilize green belts for natural trapping of both sediment and nutrient.

I-E: Prohibition of any further finger canal construction. It was obvious from the current paleolimnological investigations that construction of finger canals as part of a new residential development along the southwestern shore of Lake Manitou vastly increased the sedimentation of both inorganic sediments and phosphorus in the lake. While the impact appears to have been of relatively short temporal duration, it must be remembered that eutrophication is an additive process. Because this even could be identified clearly, it is considered to be one of the significant events in the eutrophication history of this lake. The adverse impact of finger canal construction for residential development was also clearly demonstrated for Lake Maxinkuckee by Crisman (1986b). Even today, long after the initial impact from increased inorganic sediment deposition has ended, the canals at Maxinkuckee flushed, subject to algal blooms, and generally associated with poor water quality. Further development of finger canals in the Lake Manitou watershed must be stopped at all cost.

II-A: Protection and possible restoration of wetlands. As stated earlier in this report, wetlands function as a kidney for the lake by filtering out and trapping both inorganic sediment and nutrients before they can enter the lake. Applied ecologists now recognize the extreme importance of wetlands to the proper functioning of lake systems, and their restoration and preservation are included where possible in all lake management plans. Crisman (1986b) clearly demonstrated the impact of wetlands on the eutrophication of Lake Maxinkuckee. Once this filter was removed, inorganic sedimentation increased by 39 percent and there was a pronounced increase in phosphorus loading to the lake. While an excellent effort has been made at Lake Manitou to preserve wetlands at the south end of the lake, every avenue must be explored to protect all wetlands along the lake as well as restoring wetland vegetation along slow moving reaches of streams and the upstream ends of both Mt. Zion Millpond and Millark Millpond. This is the cheapest and most natural way to trap erosion material before it enters the lake to promote further eutrophication.

II-B: Elimination of large scale weed control practices. Due to its shallow nature, Lake Manitou has always supported a lush growth of aquatic macrophytes. The extent of weed beds has expanded in direct response to the loading rate of phosphorus from the watershed. Only recently have weeds been considered a problem as a result of their growth response to increased phosphorus concentrations. It is interesting to note that the weeds have been able to keep pace with the increased phosphorus loading without leaking sufficient phosphorus to promote a serious bloom of algae in the open water. This is most fortunate because algal dominated lakes are the most difficult to manage. In Lake Manitou, the weeds are successfully competing with the algae and are able to trap the nutrients as they are being loaded to the lake. Removal of weeds releases the nutrients contained in their tissue as well as destroys the ability of this vegetation to trap phosphorus before it enters the water column. The result is obvious. By increasing nutrient availability, algal growth is stimulated in the open water areas of the lake and serious blooms result. Enhanced algal biomass then acts to shade the remainder of the weed beds, and they die out from light limitation. Once weed beds are eliminated, their restoration becomes extremely difficult. This scenario has been repeated in lakes worldwide and has resulted in serious management problems (Crisman 1986a). Lake Manitou already has an algal assemblage dominated by blue-green algal taxa considered problem producing and reduced midsummer water clarity due to algal biomass places the lake in the category of poor water quality. Thus, there is a delicate balance between weeds and algae in the lake that can easily be upset in favor of the algae as a result of even a slight disruption of the present weed beds. Continuation of the post-1980 practice of treating approximately 66 percent of the shoreline with chemicals to reduce weeds will in a short period of time tip the balance toward algal dominance. This management practice must be stopped until action is taken to control the delivery rate of erosion material from the watershed. Even then, radical treatment of weed beds must be avoided. It is suggested that future treatment of weeds concentrate on small areas for any individual treatment with chemicals, with treatment of several such areas being spread over the entire growing season.

II-C: Maintenance of DNR fish stocking program. In spite of progressive eutrophication, recent management practices of DNR have greatly enhanced the sport fishing potential of the lake. Strong support should be given to this effort. Although walleye stockings have not been as successful as northen pike, the stocking of such predator fish species may prove useful at keeping the gizzard shad population in check. Reduction in shad populations decreases predation on their principal food, large zooplankton. Such large zooplankton are the main grazers of algae in temperate zone lakes such as Lake Manitou. Both Shapiro and Wright (1984) in Minnesota and Crisman (1986c) in Florida have demonstrated how enhanced zooplankton populations following removal of their principal fish predators have proven effective at eliminating algal blooms even in highly eutrophic lakes. Such biomanipulation using fish may help to lessen the consequences of cultural eutrophication by keeping algae biomass low in spite of high nutrient levels.

III-A: Do not fertilize lawns. Fertilizer application to lawns is another source of nutrient loading to the lake. Lake water is sufficiently rich in nutrients to support lawn growth. The practice of irrigating with lake water is not only cheaper than fertilizer, but it adds no new nutrients to the lake.

III-B: Do not remove shoreline vegetation. The emergent grasses and cattails growing along the shore as well as the submergent weeds not only reduce shoreline erosion by waves generated by powerboats but also trap nutrients before they enter the water column of the lake.

III-C: Do not dredge dock areas. Mechanical mixing of sediments acts to promote release of trapped nutrients.

III-D: Minimize wave generation by boating activities. Do not ski within 200 feet of shore and lower boat speed within 400 feet of shore to a speed that minimizes wave generation. Not only do waves promote shoreline erosion, they increase the general mixing depth of the lake thus increasing recycling of nutrients.

The restoration of Lake Manitou will be a long process. Even by controlling the residential nutrient input as a consequence of the new sewer system under construction, the lake will likely show no noticeable improvement until the massive loading of inorganic sediments and phosphorus from the watershed is stopped. As stated earlier, the latter can be effectively controlled by renovating existing artificial ponds on Rain Creek, creating new retention ponds at stream mouths, and restoring wetlands. These actions were summarized as part of recommendation category I. Until external nutrient and sediment loadings to the lake are stopped, the actions proposed as part of categories II and III will have little long term effect on water quality.

Recommendation categories II and III are designed to reduce nutrient recycling within Lake Manitou proper. Of all the recommendations outlined in these categories, control of aquatic weeds is the keystone for successful future management of the lake system. The practice of radical whole lake treatment of weeds must be stopped until the measures of category I are implemented. It can not be overemphasized that if the lake shifts to algal dominance, then the cost of restoration will increase dramatically. It is much better to tolerate a short term problem (weeds) for the long term success of lake restoration.

Finally, the residents of Lake Manitou must realize from the outset that lake restoration is a long term committment and that even after eliminating nutrient loadings to the lake, there will be a long lag time before a pronounced improvement in lake water quality will be seen. This lake has always been naturally eutrophic to some degree and will remain so even after lake restoration efforts are completed. That is not to say that water quality can not be improved to acceptable levels for recreational activities. We can return the water quality of Lake Manitou to pre-1900 levels but the process will be lengthy. Every year that action is delayed on controlling the massive loadings from the watershed, however, not only lengthens the time needed for the entire restoration process but reduces the likelihood of its success. Action is needed now.

ACKNOWLEDGEMENTS

I want to extend my sincere thanks to John Winters and Harold BonHomme of the Indiana State Board of Health, Bob Robertson of the Indiana Department of Natural Resources, Dan Rosswurm of the Fulton County Soil and Water Conservation District, Wesley Burden of the Fulton County Health Department and Bob Daake, Fulton County Surveyor for access to unpublished data and out of print reports. Dr. Mike Binford of Harvard University assisted in calculation of 210-Pb dates. Not only I, but the entire Lake Manitou Association, owe special thanks to Dave Herbst for spearheading and coordinating this project. Without his assistance this effort would not have been possible. We are appreciative to Dave Herbst and Jack Overmyer for assisting in the coring operation and to the latter for supplying the boat needed for its completion. Finally, I want to thank members of my family for their devotion to my research effort. My parents, Roy (deceased) and Dorothy, helped with subsampling of sediment cores for transport to Florida. Above all, I wish to give special thanks to my wife, Ulrike,

who helped in all phases of the project including sediment coring, data collection and analysis and report preparation.

REFERENCES

American Public Health Association. 1980. Standard methods for the examination of water and wastewater. 16th edition. Washington, D.C., 1193 pp.

Andersen, J.M. 1976. An ignition method for determination of total phosphorus in lake sediments. Water Res. 10: 329-331.

Binford, M.W., E.S. Deevey, and T.L. Crisman. 1983. Paleolimnology: Historical perspective on lacustrine ecosystems. Ann. Rev. Ecol. Syst. 14: 255-286.

Crisman, T.L. 1978. Interpretations of past environments from lacustrine animal remains. pp. 69-111. IN: D. Walker (ed) Biology and Quarternary Environments. Australian Academy of Sciences, Canberra. 264 pp.

Crisman, T.L. 1986a. Eutrophication control with an emphasis on macrophytes and algae. IN: N. Polunin (ed) Ecosystem Theory and Application. Wiley Press. pp. 200-239.

Crisman, T.L. 1986b. Historical analysis of the cultural eutrophication of Lake Maxinkuckee, Indiana. Lake Maxinkuckee Association. 141 pp.

Crisman, T.L. 1986c. Algal control through trophic-level interactions: investigations at Lakes Wauberg and Newnans, Florida. Report submitted to Florida Department of Natural Resources. 142 pp.

Crisman, T.L. 1987. The use of subfossil benthic invertebrates in aquatic resource management. American Society for Testing and Materials (ASTM), Special Technical Publication, Application of Paleoecological Methodology to the Analysis of Environmental Problems. (In Press).

Crisman, T.L. and U.A.M. Crisman. 1987. Analysis of chaoborid remains from the surface sediments of Florida lakes. Verh. Internat. Verein. Limnol. 23: (In Press).

Crisman, T.L. and H.M. Kennedy. 1981. The role of gizzard shad (Dorosoma cepedianum) in eutrophic Florida lakes. Publication 64, Florida Water Resources Research Center, University of Florida, Gainesville. 83 pp.

Crisman, T.L. and U.A.M. Crisman and M.W. Binford. 1986. Interpretation of bryozoan microfossils in lacustrine sediment cores. Hydrobiologia (In Press).

Dillon, P.J. and F.H. Rigler. 1974. The phosphorus-chlorophyll relationship in lakes. Limnol. Oceanogr. 19: 767-773.

Eakins, J.D. and R.T. Morrison. 1978. A new procedure for the determination of lead-210 in lake and marine sediments. Int. J. Appl. Radiation and Isotopes. 29: 531-536.

Indiana Stream Pollution Control Board. 1980. Indiana lake classification system and management plan. 178 pp.

Stahl, J.B. 1959. The developmental history of the chironomid and Chaoborus faunas of Myers Lake. Invest. Indiana Lakes and Streams. 5: 47-102.

Shapiro, J. and D.I. Wright. 1984. Lake restoration by biomanipulation: Round Lake, Minnesota, the first two years. Freshwater Biology 14: 371-383.

Wetzel, R.G. 1975. Limnology. Saunders Press, Philadelphia, PA. pp 767.